TECHNICAL AND OPERATIONAL GUIDANCE (TECHOP)

TECHOP (D-13 – Rev1 – Sep26)

METHODS FOR PROVING THE FAULT RIDE-THROUGH CAPABILITY OF DP VESSELS WITH LV AC AND DC POWER PLANT

September 2026

DRAFT FOR REVIEW

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SUMMARY

This MTS TECHOP provides guidance on demonstrating the fault ride-through capability of low voltage (LV) alternating current (AC) and direct current (DC) power systems on dynamic positioning (DP) vessels. It is intended for vessel owners, shipyards, surveyors, system designers, equipment suppliers and those responsible for the verification and validation of DP systems.

The objective is to build a basis of confidence that a fault will not cause the loss of more equipment or station keeping capability than the redundancy concept allows. The TECHOP describes what should be examined to achieve this, the contribution and limitations of the different forms of evidence, and how that evidence can be kept valid throughout the life of the vessel.

The guidance applies to newbuilds and vessels in service. It does not require any particular test to be carried out. It recognises the potential impact of testing on LV equipment and promotes a proportionate combination of analysis, suitable existing evidence and, where appropriate, testing, so that the required level of confidence is achieved without unnecessary duplication or exposure of equipment to fault duty.

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ABBREVIATIONS

AC	Alternating current
ACB	Air circuit breaker
ASOG	Activity specific operating guidelines
APSP	Additional Power Systems Protection
AVR	Automatic voltage regulator
BITE	Built-In Test Equipment
CAM	Critical activity mode
CT	Current transformer
COMTRADE	Common format for transient data exchange
C³EI²	Cross-connections, commonality, external interfaces and influences
DC	Direct current
DP	Dynamic positioning
DPSI	DP system integration
EBCV²	Evidence based comprehensive verification and validation
ELV	Extra low voltage
ESS	Energy storage system
FMEA	Failure modes and effects analysis
FRT	Fault Ride Through
HIL	Hardware in the loop
HV	High voltage
IAS	Integrated automation system
IEC	International Electrotechnical Commission
IMCA	International Marine Contractors Association
IMO	International Maritime Organization
JDP	Joint development project
LV	Low voltage
MBT	Model Based Testing
MCB	Miniature circuit breaker
MCCB	Moulded case circuit breaker
MSF	Marine Safety Forum
MTS	Marine Technology Society
MTS DPC	MTS DP Committee
OCIMF	Oil Companies International Marine Forum
OEM	Original equipment manufacturer
PMG	Permanent Magnet Generator
PMS	Power management system

PTO	Power take-off
PTI	Power take-in
RACI	Responsible, accountable, consulted and informed
RCPD	Redundancy concept philosophy document
RTS	Real time simulation
SSCB	Solid-state circuit breaker (IEC: semiconductor circuit-breaker)
TAM	Task appropriate mode
THD	Total harmonic distortion
UPS	Uninterruptible power supply
USCG	United States Coast Guard
VMS	Vessel management system
VSD	Variable speed drive
VT	Voltage transformer
WCFDI	Worst case failure design intent

1 INTRODUCTION

1.1 PREAMBLE

1.1.1 The guidance documents on DP (Design and Operations and People) were published by the MTS DP Technical Committee in 2011, 2010 and 2012, respectively. Subsequent engagement has occurred with:

- Classification Societies (DNV, ABS)
- United States Coast Guard (USCG)
- Marine Safety Forum (MSF)
- Oil Companies International Marine Forum (OCIMF)

1.1.2 Feedback has also been received through the comments section provided in the MTS DP Technical Committee Web Site.

1.1.3 It became apparent that a mechanism needed to be developed and implemented to address the following in a pragmatic manner:

- Feedback provided by the various stakeholders.
- Additional information and guidance that the MTS DP Technical Committee wished to provide and a means to facilitate revisions to the documents and communication of the same to the various stakeholders.

1.1.4 The use of Technical and Operations Guidance Notes (TECHOP) was deemed to be a suitable vehicle to address the above. These TECHOP notes will be assigned the following categories:

- General TECHOP (G)
- Design TECHOP (D)
- Operations TECHOP (O)
- People TECHOP (P)

1.2 TECHOP NAMING CONVENTION

1.2.1 The naming convention, TECHOP (CATEGORY (G / D / O / P) – Seq. No. – Rev. No. Month Year) TITLE, will be used to identify TECHOPs, as shown in the examples below:

- TECHOP (D-01 - Rev1 - Jan21) Addressing C³EI² to Eliminate Single Point Failures
- TECHOP (G-02 - Rev1 - Jan21) Power Plant Common Cause Failures
- TECHOP (O-01 - Rev1 - Jan21) DP Operations Manual

Note: *Each category will have its own sequential number series.*

1.3 MTS DP GUIDANCE REVISION METHODOLOGY

1.3.1 TECHOPs as described above will be published as relevant and appropriate. These TECHOPs will be written in a manner that will facilitate them to be used as standalone documents.

1.3.2 Subsequent revisions of the MTS Guidance documents will review the published TECHOPs and incorporate as appropriate.

1.3.3 Communications with stakeholders will be established as appropriate to ensure that they are notified of intended revisions. Stakeholders will be provided with the opportunity to participate in the review process and invited to be part of the review team as appropriate.

2 SCOPE, DEFINITIONS & IMPACT

2.1 PREAMBLE

2.1.1 This TECHOP provides general high-level guidance and is intended to be read by vessel owners, shipyards and those providing services in relation to fault ride-through capability. Lessons learned from loss of position incidents have been summarised within the guidance documents published by the MTS DP Committee (Design, Operations and Development of People and various TECHOPs).

2.1.2 One of the key lessons learned was that DP Equipment Class requirements needed to be supplemented with a focus on the Industrial Mission. This focus brought to light the need to understand the activities being performed and the consequences of loss of position.

2.1.3 This understanding led to the development of the concepts of Critical Activity Mode (CAM) and Task Appropriate Mode (TAM). The objectives of CAM are to achieve the highest level of station keeping integrity and enhance the predictability of failure consequences.

2.1.4 Achieving the highest level of station keeping integrity on DP is influenced by what is referred to in the MTS Guidance documents as the seven pillars:

1. Autonomy.
2. Independence.
3. Segregation.
4. Differentiation.
5. Fault tolerance.
6. Fault resistance.
7. Fault ride through.

2.1.5 The guidance documents address these seven pillars, the influence they have, the consideration that is needed in areas of Design, Operations and People, and the importance of thorough analysis supported by effective verification.

2.1.6 A means of achieving the objectives of the seven pillars was to operate diesel electric power plants in a default configuration of two or more independent power systems (open bus ties) and to avoid cross connections of any nature between redundancy groups. Post failure capability governed operating limits and criteria. A consequence of operating in such configurations was a requirement for a larger number of engines online, usually operating on low loads, with a detrimental effect on the vessel's emissions footprint.

2.1.7 Requirements to reduce emissions are one reason for considering other configurations, including the interconnection of otherwise independent power systems. Any benefit should be weighed against what is needed to maintain station keeping integrity in that configuration.

2.1.8 When the principles of autonomy, independence and segregation are compromised (for example by closed bus ties or by cross connections of any nature between redundancy groups), greater emphasis is needed on demonstrating fault tolerance, fault resistance and fault ride-through.

2.1.9 Industry experience has shown that DP FMEA proving trials and annual DP trials, as normally conducted, may not demonstrate fault ride-through capability in every operating configuration. The FMEA and the associated studies should identify where further evidence is needed to build confidence in that capability.

2.1.10 Where a fault occurs, the faulted equipment may be lost within the worst case failure design intent (WCFDI). The remaining equipment should keep the performance needed for station keeping. Restarting equipment that is intended to remain available is not an acceptable substitute for adequate fault ride-through, because it introduces delay and uncertainty into the recovery of DP critical functions, unless it is permitted by aegis of specific Class notations and their qualifiers.

2.1.11 Substantiating and corroborating evidence to support single fault tolerance should address the disturbance seen by the surviving equipment, the action of the protection system and the resulting effect on station keeping. Relevant fault types include short circuits, earth faults, unbalanced faults and arcing faults, depending on the installed arrangement.

2.1.12 This TECHOP gives guidance on building confidence in the fault ride-through capability of LV power systems. It pays particular attention to arrangements that connect redundancy groups, and it also applies where the main bus ties are open but other paths (power couplings / transfer etc.) remain by which a disturbance can affect more than one group. The TECHOP does not exclude other credible means of demonstrating fault ride-through capability.

2.2 DEFINITIONS

2.2.1 The following definitions apply in this TECHOP.

Note: *Definitions invoked through statutory instruments or contractual documents prevail.*

Automation-system terminology: In this TECHOP, the integrated automation system (IAS) means the overall integrated automation environment and may include the DP control system, power management system (PMS), vessel management system (VMS), machinery automation, alarm and monitoring functions, and their associated networks and interfaces. The VMS means the vessel remote-control and supervisory system for machinery and other vessel functions. Depending on the installed architecture, the VMS may include the PMS or may interface with a separate PMS. The terms IAS, VMS, PMS and DP control system are therefore not interchangeable. The assessment should identify the functions implemented within each system and the dependencies and interfaces between them for the vessel concerned.

2.2.2 **Additional Power Systems Protection (APSP):** Supplementary protection functions used to detect and limit the consequences of governor, excitation, load-sharing or source-control failures before those failures cause loss beyond the worst case failure design intent. The functions and quantities used by APSP depend on the installed power-system architecture and should be assessed for the actual AC or DC arrangement.

2.2.3 **Attribute:** A characteristic or capability of the installation on which the redundancy concept depends. Examples are the isolation of a fault, the continued availability of a healthy control supply and the retention of the required thrust. Attributes can be lost or degraded in service, so the evidence should show both that the attribute exists and what is needed to keep it effective.

2.2.4 **Basis of confidence:** The reasoned case, supported by evidence, that the required attributes are present and will be available when needed. It should allow a reviewer to see what is concluded, which configurations are covered, what evidence supports the conclusion, what limitations remain, how loss or degradation of a required attribute will be detected and when further verification will be needed.

2.2.5 **Disturbance envelope:** A description of the electrical disturbance that equipment at a defined point of use is expected to withstand. For AC systems this normally covers the depth and duration of the voltage reduction or interruption, the recovery profile including any overshoot and, where relevant, the frequency excursion and phase displacement. For DC systems it normally covers the voltage variation, its rate of change and duration, and the recovery. The envelope is derived from the fault studies and the protection performance, including the applicable protection failure case.

2.2.6 **Fault barrier:** An arrangement relied upon in the redundancy concept to prevent a fault on one side of it from causing a failure effect on the other. A fault barrier is relied upon for a particular arrangement in particular operating states and needs evidence specific to that arrangement.

2.2.7 **Fault ride-through:** The capability of the equipment and systems required after a fault to continue their required function during the disturbance, its clearance and the recovery. This is consistent with the use of the term in TECHOP D-07. The period of interest runs until the surviving system has settled, and the measure of success is continuity of the required function.

2.2.8 **Point of use:** The terminals of the equipment performing a required function. The disturbance at the point of use may differ considerably from that at the location of the fault, because of intervening voltage levels, conversion equipment, protection and stored energy.

2.2.9 **Required surviving function:** The function that equipment (which required or intended to remain available) must deliver during the disturbance, its clearance and the recovery. It is expressed as the output the redundancy concept needs, for example the thrust available at the propeller. Continued energisation of an item, or the absence of a trip, is not the same as delivery of the required function.

2.2.10 **Semiconductor circuit breaker (solid-state circuit breaker, SSCB):** A circuit breaker designed to make and interrupt current through the controlled conductivity of semiconductor devices. Mechanical contacts may also form part of the complete device. In this TECHOP, the widely used term solid-state circuit breaker and the abbreviation SSCB are retained.

2.3 SCOPE

2.3.1 This TECHOP provides information pertinent to Fault Ride Through capability of LV systems expanding on themes of:

- The benefits and drawbacks of “hard” and “soft” ties.
- Typical LV system topologies.
- Power system attributes that support fault ride-through.
- The contribution and limitations of analysis, modelling and the various test methods.
- Planning, conducting and reporting tests, where testing is selected as part of the evidence.
- Network and control system considerations.
- Maintaining the basis of confidence through the life of the vessel.

2.3.2 The scope includes LV AC and DC generation and distribution, together with the supplies on which DP critical equipment depends. Examples are 440 V or 690 V AC power systems, 120 V or 230 V AC auxiliary supplies and 24 V DC control supplies. These are examples, not voltage limits. Definitions of low voltage and extra low voltage (ELV) should follow the applicable standards. ELV services are within the functional scope where their failure can affect DP capability.

2.3.3 The assessment of FRT capability should follow the supply path from the source to the equipment performing the required function, including conversion, UPS or battery support, distribution protection, controls, auxiliaries and the relevant return or earthing paths. An item should not be left out because it carries little power or is supplied from a different voltage level.

2.3.4 On vessels with HV generation and distribution, TECHOP D-07 addresses the HV plant.

2.3.5 This TECHOP applies to vessels whose main power plant is LV and to the LV distribution, auxiliary supplies and control supplies on which the DP critical equipment depends. Thus this TECHOP applies to the relevant LV parts within all DP vessel power plants.

2.3.6 Figure 2-1 shows the functional dependencies behind useful thrust and illustrates why the assessment should follow the complete path. The assessment for a particular vessel should identify the separate and shared supporting services on which the required equipment depends.

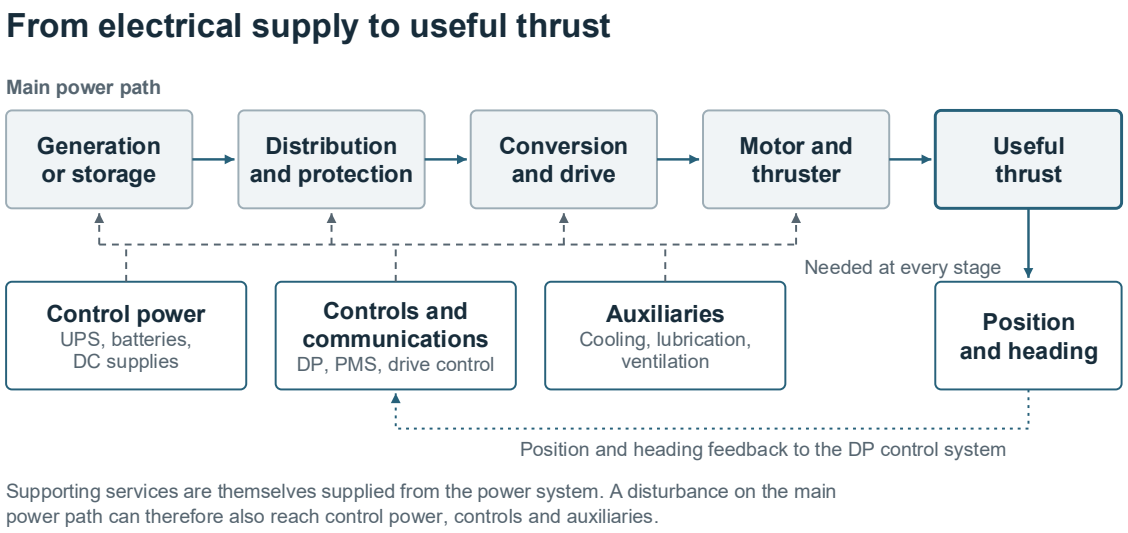


Figure 2-1 Functional dependencies supporting useful thrust

2.4 FOCUS OF THIS TECHOP

2.4.1 The focus of this TECHOP is demonstrating fault ride-through capability in LV power systems. It should be read together with TECHOP D-07, “A Method for Proving Fault Ride-Through Capability of DP Vessels with HV Power”, which addresses HV plant.

2.4.2 Fault ride-through capability is a significant part of the fault tolerance of a DP power plant. It becomes more significant where the principles of independence and segregation are not followed, because a lack of fault ride-through capability can then lead to loss of position.

2.4.3 For the same power, a lower system voltage means a higher load current. This is the challenge that needs to be overcome in low voltage power systems (AC and DC). The fault current and the resulting effect on equipment depends on the connected sources, the system impedance, converters and protection. LV plant can therefore experience high fault levels which may limit how often equipment can survive such faults without damage. On the other hand, current limited sources may not provide sufficient current for conventional protection to clear a fault quickly. Both conditions should be considered and addressed.

2.4.4 Loss of position can also result from other failure modes in power plants operating with bus ties closed, for example:

- Generator fuel control system failures.
- Generator excitation control system failures.
- Failures of harmonic cancellation facilities that lead to Total Harmonic Distortion (THD) levels with the potential for resonance or other undesirable effects.
- Load sharing system failures.
- Power Management System failures.
- Switchboard component degradation.

2.4.5 These failure modes are addressed in other TECHOPs and in the MTS DP Vessel Design Philosophy Guidelines. Their relevance depends on the installed architecture. A power electronic converter based interconnection may remove or limit some propagation mechanisms and introduce others. This should be established by the failure analysis for the arrangement concerned.

2.4.6 Development of hypotheses for analysis and simulated faults for application to the power system for verification, validation, and assurance at live testing and MBT should consider the dynamics of fault development and ensure that the range of fault types applied is representative of the worst conditions including attributes such as magnitude, rate of change and duration.

2.5 VERIFICATION BY TESTING

2.5.1 This TECHOP’s purpose is to describe what should be examined in order to build a basis of confidence in single fault tolerance, and the contribution and limitations of the evidence that may be used. It is emphasised that nothing in this TECHOP is intended to require the application of a fault to LV plants for validation by testing purposes.

2.5.2 Where live short circuit testing is selected / required as part of the evidence, the following pre-requisites apply:

- The equipment should be designed and built to allow testing or be of a design and construction that allows safe and effective verification by testing.
- It should be confirmed that the equipment to be tested is suitable, within the Original Equipment Manufacturer (OEM) specifications, for the proposed test.

- Risk assessments and the associated mitigations should be comprehensive to establish confidence that the test can be carried out safely.
- The testing should be undertaken by organisations with the necessary technical knowledge, operational experience, tools and competent resources.

2.5.3 A series of pre-tests using different methods should be carried out before a more onerous test, to build confidence that it will produce a successful outcome. Section 9.2 lists the commissioning evidence that commonly forms part of that preparation.

2.5.4 Testing should be carried out only when there is adequate confidence that it can be done safely, and that confidence should be substantiated and corroborated by documentation at an appropriate level of detail.

2.5.5 No vessel owner should feel under pressure to carry out a test they consider unsafe.

Note: *Vessels that cannot establish single fault tolerance through validation testing are expected to operate in configurations that are single fault tolerant commensurate with the industrial mission and the consequences of a loss of position. MTS DPC guidance has embedded the above objective through the concepts of CAM and TAM and the build to test philosophy.*

2.6 RELATIONSHIP TO CLASS, STATUTORY AND CONTRACTUAL REQUIREMENTS

2.6.1 Nothing in this TECHOP is intended to exclude a DP vessel from undertaking an industrial mission. The suitability of a DP vessel to undertake its Industrial Mission is determined by a number of stakeholders, including owners, statutory authorities and charterers and may be stipulated by the specific DP equipment class notation and additional requirements (if any) under contractual obligations.

2.6.2 The applicable Class, statutory and contractual requirements, and the intended CAM or TAM configuration, should be identified before the verification basis is agreed. Where an alternative method of verification is proposed, it should be considered against those requirements.

Note: *IMO MSC/Circ 645 and MSC.1/Circ.1580, provide for bus tie breakers to be open during equipment class 3 operations unless equivalent integrity of power operation can be accepted in accordance with that guidance. Fault ride-through evidence may provide part of the evidence for equivalent integrity. Verification by analysis and testing is part of the process of building confidence in the single fault tolerance of a DP system. The relevant failure criteria are those of the vessel's equipment class and design basis. The fault ride-through evidence should show that failure effects remain within the WCFDI and that the surviving generation, thrusters and supporting systems can provide the required station keeping capability.*

2.7 IMPACT ON PUBLISHED GUIDANCE

2.7.1 This TECHOP provides guidance on fault ride-through in LV systems. TECHOP D-07 remains applicable to HV systems, and this TECHOP develops the LV approach introduced in Section 10.2 of TECHOP D-07.

2.7.2 This TECHOP provides supplementary information to that in Section 11.2 of the MTS DP Vessel Design Philosophy Guidelines (2021) and does not alter or invalidate that section.

2.7.3 This TECHOP should be read with:

- TECHOP D-02, FMEA Testing
- TECHOP D-01, Addressing C³EI² to Eliminate Single Point Failures

- TECHOP D-03, Blackout Recovery
- TECHOP D-04, Evaluation of Protection Systems
- TECHOP G-02, Power Plant Common Cause Failures

2.7.4 Where this TECHOP addresses a subject covered by one of those documents, it does so in relation to fault ride-through in LV systems and does not change the guidance given therein.

2.7.5 Where a method proposed under this TECHOP differs from an applicable testing requirement or an agreed verification basis, its adequacy and acceptance should be resolved with the responsible stakeholders.

2.8 HOW TO USE THIS TECHOP

2.8.1 Sections 3 to 6 explain the case for action and the attributes to be demonstrated. Section 7 covers practical considerations, including the burden of verification. Section 8 addresses modelling. Sections 9 and 10 apply where testing forms part of the evidence, and Section 11 covers reporting and the handover of the basis of confidence. Section 12 compares the available methods, and Section 13 covers networks and controls. Section 14 brings these together in an implementation and continuing verification strategy. Section 16 gives worked examples.

Note: *It is emphasised that preservation of fault ride through capability is expected to be verified, validated and assured throughout the life cycle of a DP vessel. A successful test at delivery needs to be augmented by periodic verification, validation and assurance of perishable attributes of performance, protection and detection upon which single fault tolerance relies.*

2.9 ACKNOWLEDGEMENTS

2.9.1 The DP Committee of the Marine Technology Society greatly appreciates the contributions of ABB, ABS, DNV, OneStep Power and Siemens Energy to the preparation of this TECHOP.

3 CASE FOR ACTION

3.1 RECENT INDUSTRY EXPERIENCE

3.1.1 DP incidents have shown that inadequate fault ride-through can turn a local electrical fault into a wider loss of power or thrust. Correct operation of the main protection does not prevent this if healthy consumers, or the systems supporting them, cannot tolerate the disturbance. Verification should therefore address both fault clearance and the functions that the surviving equipment is expected to retain if loss of position is not to occur.

3.1.2 The following failure mechanisms are typical of LV plant. In each case the fault was detected and isolated as designed, but the consequence still exceeded the WCFDI:

- **Loss of auxiliaries during a cleared fault.** A fault is cleared within the graded time, but contactors supplying cooling, lubrication and ventilation services drop out during the voltage dip. The generators and drives ride through but the auxiliaries do not. Station keeping is lost some seconds or minutes later on a delayed auxiliary trip, which may not be immediately associated with the electrical event.
- **A branch fault on a shared control supply.** A fault on one branch of an LV or extra low voltage (ELV) control distribution, such as a 24 V DC control supply, pulls down the common supply because the source goes into current limit before the branch protective device operates. Healthy control functions on the same distribution are lost, in more than one redundancy group where the distribution is shared or cross fed.
- **UPS behaviour during the disturbance.** A UPS supporting DP control, position reference or protection control power, fails to hold its load through a transfer, or is found to have been running on bypass, or current limits below the pickup of a downstream protective device so that a fault on an outgoing circuit is not cleared.
- **A required barrier that did not contain or isolate the fault.** An interconnection credited with limiting fault transfer between sections, commonly a converter, fails to do so because the failure occurred in a mode, direction, bypass state or control condition outside the arrangement on which the conclusion of fault isolation was based.
- **Too little fault current for prompt clearance.** A current limited source, or an arcing fault, produces a fault current below the pickup of the protection credited with isolating it. The fault persists and the disturbance spreads beyond the section in which it occurred.

3.1.3 The above-mentioned mechanisms have two things in common. First, the power system performed as designed and the consequence arose in the auxiliary, control or stored energy arrangements on which the required function depended. Second, the arrangement had been verified, but not in the operating mode or configuration in which it failed. The scope of verification should therefore follow the functional dependencies of the required surviving function, and the basis of confidence should state the operating modes and configurations to which it applies.

3.2 HARD TIES (DIRECT LOW-IMPEDANCE CONNECTIONS, E.G. CLOSED BUS TIES)

3.2.1 In this TECHOP, a hard tie is a direct low-impedance conductive connection between power system sections. The connection may be formed by busbar, cable or another type of conductor through an associated mechanical, combined or solid-state switching device. When the tie is closed or conducting, the sections are directly connected without an intervening power-electronic conversion stage. A semiconductor circuit breaker, commonly referred to as a solid-state circuit breaker (SSCB), used in this way forms part of a hard tie; it is a switching and interruption device, not a power-electronic converter.

3.2.2 The verification and validation burden that comes with hard ties should be understood at the design stage. The aim is to establish sufficient evidence of fault clearance and surviving system performance, and then to keep that evidence valid. Existing records, condition monitoring, maintenance and targeted testing may all contribute to the basis of confidence in the efficacy of the protection scheme. The scope should follow the attributes relied upon and the ways in which their effectiveness could be lost.

3.3 SOFT TIES (POWER-ELECTRONIC CONVERTER CONNECTIONS)

3.3.1 In this TECHOP, a soft tie transfers power between power system sections through one or more power-electronic converters and does not create a direct low-impedance conductive connection between the sections. In this arrangement, the converter arrangement is designed to prevent the full effects of a fault from propagating; it can reduce the disturbance on the healthy section and the fault ride-through duty on the equipment there. The extent of this benefit should be demonstrated for the actual arrangement, directions of power flow, operating states and relevant failures.

3.3.2 Calling an interconnection a soft tie does not make it a fault barrier. The analysis should address power flow in both directions, converter failure, bypass or alternative feed paths, and shared controls or supporting services. Equipment should still have adequate fault ride-through for any disturbance that can reach its terminals.

3.3.3 Soft ties using DC links may make it easier to integrate energy storage if it is part of the design objective.

3.3.4 Factory and commissioning evidence can establish the initial performance of a required barrier. The continuing verification strategy should identify which attributes depend on settings, software, active protection, condition or maintenance, and how each will be kept valid. Where a barrier reduces the need for intrusive testing, confidence in the barrier itself still has to be maintained.

4 FAULT RIDE-THROUGH EVIDENCE IN DP SYSTEM VERIFICATION & VALIDATION

4.1 HOW FAULT RIDE-THROUGH EVIDENCE FITS WITHIN VERIFICATION AND VALIDATION

4.1.1 Methods used to prove the fault ride-through capability of HV systems may not transfer directly to LV systems. The choice of evidence should take account of the actual fault duty, the equipment ratings and condition, and the effect of repeated exposure. The required level of confidence should be kept even where a different means of verification is needed.

4.1.2 Verification and validation activities should be developed on an engineering basis for the chosen design and test objectives should be clearly defined and documented with the appropriate correlation to the attributes of performance, protection and detection.

4.1.3 Fault ride-through evidence is part of the wider DP verification and validation process. A correctly designed and configured protection scheme can still allow failure effects to exceed the WCFDI if healthy equipment loses its function during fault clearance or recovery.

4.1.4 A combination of analysis and physical evidence is required to address the conclusions to be demonstrated. The basis of the choice of analysis or physical evidence should be unambiguously documented and substantiated with calculations, validated models, equipment qualification, factory and commissioning records and installed system testing. Each should be used for what it can demonstrate, with its assumptions and limitations stated.

4.1.5 The aim is to establish a coherent basis for confidence in the installed system. The relevance of each test matters more than the number or severity of tests. A representative test is useful when the analysis explains which configurations and failure cases it covers. Any material conclusion that falls outside the evidence needs to be resolved.

4.1.6 Four related conclusions should be demonstrated and documented:

1. The equipment can tolerate the disturbance at its terminals.
2. The protection system can detect and isolate the fault selectively.
3. The equipment is suitable for the electrical and mechanical duty.
4. The installed DP system retains the desired station keeping capability.

4.1.7 Evidence for one of the above mentioned conclusions should not be presented as proof of the others. For example, showing that a relay issues a trip command does not show that the fault current was interrupted or that thrust was retained. Equipment type test evidence describes the equipment. The behaviour of the complete installed power and control system needs its own evidence. Figure 4-1 gives examples of the evidence that commonly supports each conclusion.

Evidence and the four fault ride-through conclusions

Conclusion	Question answered	Typical evidence
1 Equipment immunity	Does the equipment tolerate the disturbance at its terminals?	Immunity and qualification data; disturbance at the point of use
2 Selective isolation	Is the fault detected and isolated selectively?	Protection studies; injection tests; checks of the installed trip path
3 Equipment duty	Is the equipment suitable for the electrical and mechanical duty?	Ratings and duty assessment; source characteristics; condition
4 Integrated DP function	Does the DP system keep the desired station keeping capability?	System analysis and modelling; integrated vessel response

Each conclusion needs its own evidence. Evidence for one conclusion should not be presented as proof of the others (Section 4.1).

Figure 4-1 Examples of evidence supporting a conclusion of fault ride-through

4.2 WHY LV VERIFICATION DIFFERS FROM HV

4.2.1 The reasons are set out in TECHOP D-07 Section 10.2. For a given power, a lower system voltage needs a higher current, and the prospective fault currents and electromagnetic forces in LV systems of even modest capacity are correspondingly large. LV switchboards with short circuit ratings of the order of 100 kA are common, compared with typical HV switchgear ratings of around 31.5 kA. Air circuit breakers (ACBs) in LV switchboards may be rated for a limited number of high current interruptions, in some cases only one, before inspection or overhaul is needed. Repeated application of a fault at the main distribution level is therefore not normally available as a verification method for a LV AC plant.

4.2.2 The opposite condition also occurs. Some LV arrangements are designed to limit fault current, for example by phase shifting transformers between bus sections, by impedance, or by the current limiting behaviour of converters and solid state devices. In these arrangements the available fault current may be too low for conventional protection to detect and clear promptly, and the difficulty is dependable detection. Both conditions may exist in the same installation at different points, and each should be addressed where it applies.

4.2.3 This TECHOP does not require a fault to be applied to LV plant. Where an owner considers applying a low impedance to simulate a fault, for example on a current limited power system design or at a service transformer secondary where the duty is shown to be within the rating and proven service capability of the equipment (see TECHOP D-07 Section 10.2), the conclusions it supports (and those it does not) should be identified as described in Section 12, and the effect on the equipment and its continued service should be agreed with the relevant OEM beforehand.

4.3 RELATIONSHIP TO JDP01 AND EBCV²

4.3.1 JDP01, “Unified Approach to the Verification, Validation and Assurance of Single Fault Tolerance of DP Systems”, published jointly by OCIMF, the IMCA DP Committee and the MTS DP Committee, describes Evidence Based Comprehensive Verification and Validation (EBCV²). EBCV² is a structured means of building and maintaining the evidence behind a redundancy concept, drawing on the redundancy concept philosophy document (RCPD), the DP FMEA, DP system integration (DPSI), supporting studies, validation testing and modelling.

4.3.2 The fault ride-through evidence described in this TECHOP forms part of the EBCV² evidence set. The basis of confidence defined in Section 2.2 is the fault ride-through part of that set and should be assembled, recorded and maintained so that it can be used as such.

4.3.3 JDP01 summarises the burden and application of each verification activity for DP vessels in service.

4.4 BUILD TO TEST

4.4.1 Designs should incorporate means to achieve the objective of verification and validation by testing. Due consideration of the above objective in the design can significantly alleviate the burden of verification and validation by testing.

4.4.2 The build to test philosophy in the MTS guidance means designing the installation so that the attributes required in the redundancy concept can be demonstrated at delivery and demonstrated again through the life of the vessel. For LV plant this includes:

- Access for measurement at the points of use identified in the analysis, through dedicated test interfaces with standard connectors where practical.
- Logging and recording facilities with the resolution and time correlation needed to reconstruct a disturbance.

- Identification of settings, software versions and protective devices, so that the arrangement verified can be shown to be the arrangement installed.
- Provision for applying a disturbance by a less onerous method than a low impedance, for example excitation control or a converter fed section, where that is the intended route to the evidence.
- Separation of fault paths, and equipment ratings and condition information, that allow the verification to be repeated without undue duty on the equipment.

4.4.3 Where these provisions are absent, the verification burden moves to more onerous methods with greater cost or greater residual uncertainty. Owners should establish at the design stage how each required attribute will be demonstrated initially and maintained thereafter, and should be prepared to select a different arrangement where that question cannot be answered. Sections 7.5 and 9.6 develop these points for newbuilds and for vessels in service.

5 TYPICAL TOPOLOGIES OF LV DP SYSTEMS

5.1 INTRODUCTION

5.1.1 LV power systems are used on a wide range of DP vessels. The examples in this section show features that influence fault propagation, fault clearance and the ability of the surviving equipment to keep operating.

Note: *The examples in this TECHOP are only examples. They are not intended to depict a complete design or recommend adoption of a particular topology.*

5.1.2 The topologies below differ in how readily their attributes can be demonstrated and re-demonstrated. That difference should be weighed when a topology is selected, together with the build to test provisions in Section 4.4.

5.1.3 The design and configuration of an LV DP power system largely determine its fault ride-through capability and therefore its station keeping integrity during critical operations. In LV systems the duty imposed by a fault may limit the number of exposures allowed before inspection, maintenance or replacement is needed. The limits depend on the equipment and the conditions. Mechanical, hybrid and solid-state devices should each be assessed against their ratings, supporting components and maintenance needs. No protection technology can be assumed to tolerate an unlimited number of fault operations.

Note: *The term 'duty' in this TECHOP means the performance of a system, subsystem or component, that is expected during the exposure to the fault over the life cycle of its intended use.*

5.2 AC POWER SYSTEMS

5.2.1 LV AC power systems on DP vessels can be arranged in a number of ways, depending on the size, role and design objectives of the vessel. Familiar features of AC distribution include:

- **Ease of voltage transformation:** AC systems allow straightforward conversion between voltage levels, which supports flexible distribution arrangements.
- **Established generation and conversion arrangements:** AC generators can supply AC distribution directly or supply DC distribution through rectifiers. The fault response should be assessed for the complete arrangement.
- **Auxiliary system compatibility:** AC induction motors are widely used in auxiliary systems because of their low cost and proven reliability.
- **Current interruption:** the natural current zero in AC systems helps suitably rated protective devices to interrupt fault current.
- **Voltage selection:** for the same power, a higher voltage reduces load current and may reduce conductor size. This applies to DC distribution as well.
- **Regulatory alignment:** Classification Society rules have historically been developed around AC system architectures.

5.2.2 Using established AC equipment products does not remove the need to assess the response of the complete system. Converters, energy storage and shared controls can change that response even where the main distribution remains AC.

5.2.3 Design features that may be used in LV AC systems on DP vessels include:

- **Phase shifting arrangements:** suitably designed transformer or converter arrangements can reduce low order harmonics. Where harmonic cancellation is relied upon, the analysis should establish the effect of losing it. The actual connection arrangement should be clear in the system description.

- Power take-off and power take-in (PTO and PTI): a shaft driven machine can supply electrical power from an engine or propulsion shaft, or can deliver propulsion power from the electrical plant. Its contribution and its response to a fault depend on the mechanical drive, on the conversion and protection arrangements, and on the direction of power flow at the time of the fault.

5.2.4 **Energy storage systems:** there are several ways to integrate an energy storage system (ESS) into an LV AC power system. Storage connected through a DC link needs conversion to exchange power with the AC distribution. From a fault tolerance point of view, a connection to the main bus and a connection at an individual thruster should be considered separately.

5.2.5 An ESS connected to the main bus may support power balance and voltage recovery, within the limits of its converter and protection. It is also exposed to disturbances on that bus. An ESS connected at a thruster may support continued thrust during a main supply disturbance, provided that the fault is contained and the drive, controls and auxiliaries remain available.

5.2.6 Where energy storage is connected to a thruster DC link, the ability of the storage system to transfer power back to the supplying bus depends on the installed converter arrangement. An uncontrolled rectifier prevents reverse power flow from the DC link to the AC supply. In that arrangement, the storage system provides local energy support and does not by itself create a power-transfer connection between the supplying bus sections.

5.2.7 Where a bidirectional active front-end converter is installed, power may be transferred from the DC link to the supplying bus when permitted by the converter controls and operating mode. In a dual-fed arrangement, the assessment should establish whether this creates a power-transfer path between the supplying sections. The assessment should distinguish normal or commanded power transfer from behaviour during a fault, when converter protection or current limiting may block or restrict reverse power flow.

5.2.8 The contribution that can be relied upon should be established for each relevant configuration. A local energy source or a UPS should not be taken as evidence of an independent thruster unless the complete supply and support arrangement has been assessed.

5.2.9 Energy storage and UPS arrangements are not a substitute for a fault tolerant power system. Single fault tolerance remains the foundation of the redundancy concept. Additional barriers strengthen the redundancy concept; they do not justify reduced fault tolerance in the main power system.

5.2.10 Energy storage is time limited. Where an ESS is relied upon for fault ride-through or post failure capability, the available power and usable energy should support the required function for the required period, including the time needed to terminate the activity safely where relevant. An ESS is also limited in the fault current it can deliver compared with a diesel generator of similar rating. Where an ESS is a required source, the fault current available should be established for the relevant states, together with its effect on the ability of the overcurrent protection to operate selectively (see Sections 6.12 and 6.16). IMCA M250 gives further guidance on hybrid battery systems.

5.2.11 The basis of confidence should state the conditions under which the ESS contribution is available, including limits on state of charge, state of health, temperature, and converter operation. Monitoring, maintenance, and periodic verification should keep those conditions in place throughout service.

5.2.12 Figure 5-1 shows an example of a two section LV AC arrangement including energy storage.

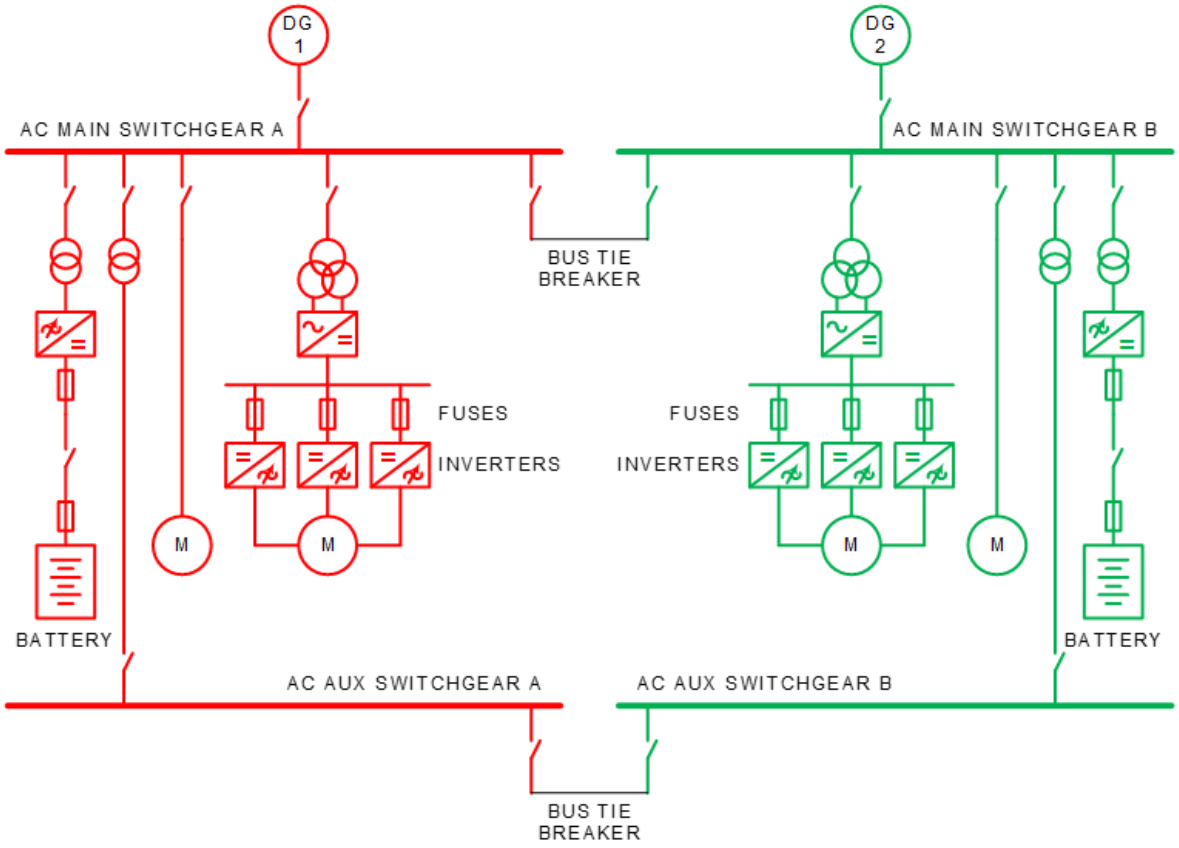


Figure 5-1 AC Topology Example 1, Two-section System, Including Energy Storage

5.3 DC POWER SYSTEMS

5.3.1 DC power systems are an alternative to conventional LV AC distribution. Power electronic devices, fuses and other protective devices may limit fault current and isolate a fault quickly. The verification approach should reflect the particular source, conversion and protection arrangements. Some AC failure mechanisms are removed, while DC energy storage, conversion, control and interruption introduce others.

Note: *In a DC system, load sharing between sources is a function of the converter controls, the automatic voltage regulators of the feeding generators or the controlled rectifiers, rather than of the engine governors as in an AC system. The failure modes affecting load sharing therefore lie in those controls.*

5.3.2 DC architectures also make it easier to integrate a broad range of energy sources, including but not limited to:

- Fixed speed and variable speed generator sets.
- Shaft generators.
- Battery energy storage systems.
- Fuel cells.
- Shore power connections and in-field charging arrangements.

5.3.3 Using different energy sources may give operational flexibility and support differentiation. The benefit depends on the common dependencies that remain, including conversion equipment, software, controls, cooling and power supplies. Different source types should not be assumed to be independent of each other.

5.3.4 The following paragraphs describe the integration of some of these sources in DC power systems. Each should be considered against the vessel's redundancy concept, together with its effect on the verification and validation burden.

5.3.5 **VARIABLE SPEED GENERATORS**

5.3.6 Variable speed generators in DC power systems may improve fuel efficiency at some operating points. Their contribution should be considered across the intended speed and load range, including their response following the loss of another source.

5.3.7 At reduced speed, the ability of a generator to accept a rapid increase in load may be limited. An ESS may help to manage that demand. Where this support is required, the analysis should show that it remains available in the relevant failure and degraded conditions.

5.3.8 **ENERGY STORAGE**

5.3.9 DC distribution makes it easier to integrate electrical energy storage. The connection may still need DC/DC conversion, isolation and protection to manage voltage, current and fault behaviour.

5.3.10 Although there is no AC synchronisation at a common DC bus, load sharing and protection are not necessarily simpler. The verification should establish stable power sharing and selective fault containment, including the behaviour of the converters and their controls.

5.3.11 Figure 5-2 shows an example of a two-section DC arrangement including energy storage.

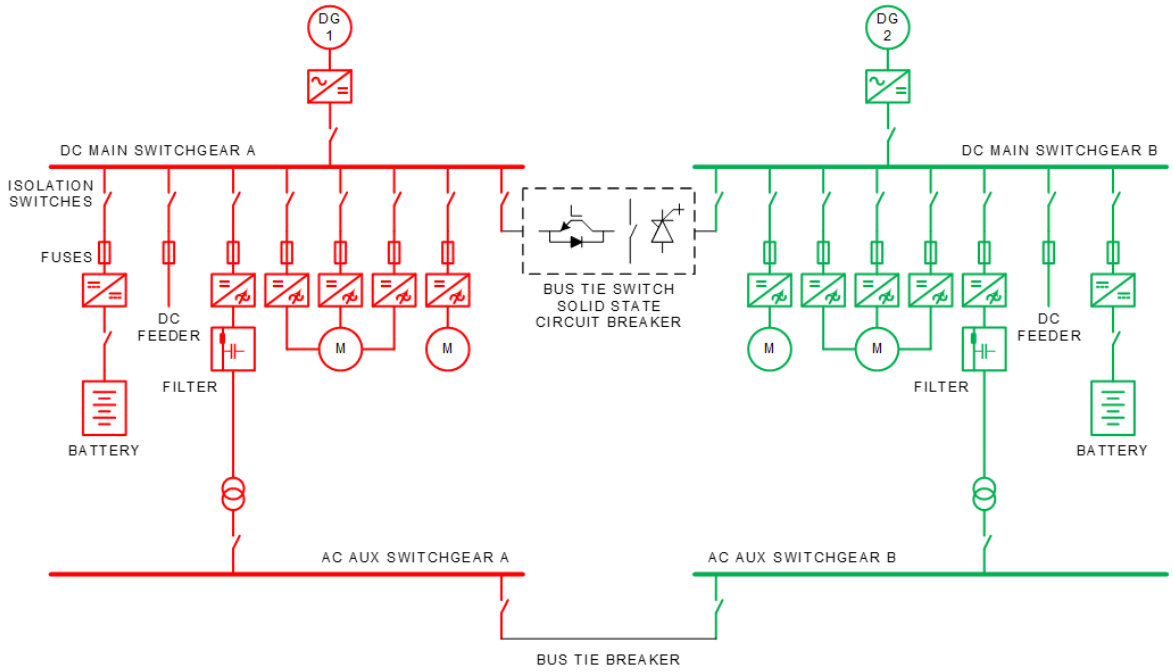


Figure 5-2 DC Topology Example 1, Two-section System, Including Energy Storage

Note: *Two independent SSCBs in series would be required for most DP notations.*

5.3.12 **SOLID-STATE CIRCUIT BREAKERS**

5.3.13 Semiconductor circuit breakers, commonly referred to in this TECHOP as solid-state circuit breakers (SSCBs), can detect and interrupt a fault quickly and may reduce the duty imposed on other equipment. Their contribution to the redundancy concept should be established for the actual device and application, together with the evidence needed to maintain confidence in that function.

5.3.14 A principal purpose of periodic testing and continuous supervision is to detect hidden failures capable of defeating the redundancy concept. An SSCB may remain closed and continue to carry normal load even though a current sensor, measurement channel, protection algorithm, gate-drive circuit, semiconductor switching path, auxiliary supply, energy-absorption component or communications interface is no longer capable of performing its required protective function. Such a failure may remain undetected until a power-system fault occurs. If the SSCB then fails to interrupt within the required time, or if the wrong SSCB operates, the fault may propagate beyond its intended fault-containment zone and cause loss of equipment in more than one redundancy group.

5.3.15 The continuing verification programme should therefore demonstrate not only that the SSCB can operate, but also that latent degradation or failure of its sensing, decision, switching and energy-absorption functions will be detected before the protection function is demanded. The programme should identify which hidden failures are detected by continuous diagnostics or built-in test equipment (BITE), which require current injection or commanded-operation testing, and which can only be demonstrated by a controlled live short-circuit test or supported by representative type-test evidence. No method should be credited beyond the part of the protection chain that it actually exercises.

5.3.16 **Controlled live short-circuit testing.** Where the installed power system, SSCB and test facility are designed for the duty, controlled application of a live short circuit provides the strongest end-to-end demonstration of the complete installed protection function. It can exercise the actual primary current path, installed sensors, protection logic, gate-drive circuits, semiconductor switching devices, energy-absorption components, auxiliary supplies and communications, while also demonstrating selectivity, coordination, fault containment and the response of the required surviving functions. Rapid SSCB interruption can limit fault current, fault energy and disturbance duration sufficiently to permit repeated, controlled on-demand tests using a purpose-designed permanent test facility. Such testing should not be characterised as inherently undesirable where the equipment is rated for the applied duty and the test arrangement, risk controls, recording and restoration provisions are suitable.

5.3.17 **Current injection.** Primary or secondary current injection provides a less disruptive means of commissioning, periodic verification and fault finding between live short-circuit tests. Primary injection can exercise the installed primary conductor, current sensor and measurement path. Secondary injection or simulated-sensor testing can verify settings, pickup thresholds, timing, protection logic and trip commands where the manufacturer provides an approved test interface. The test record should identify the point at which the stimulus enters the protection chain and the sensing, processing, trip and interruption functions that are included or bypassed.

5.3.18 Secondary injection is not practicable for every design. Current sensors, signal-conditioning circuits and controllers may be integrated into an encapsulated or sealed assembly with no accessible secondary terminals or test connector. Intrusive access may affect calibration, insulation, environmental protection, equipment certification or warranty. Where an approved secondary-injection interface is not provided, this should not itself be treated as a deficiency. The OEM should identify the approved test method, its diagnostic coverage and the parts of the protection chain that remain outside the test boundary.

5.3.19 **Built-in test equipment and continuous supervision.** BITE and continuous supervision should be designed primarily to detect hidden failures capable of defeating the redundancy concept between controlled live short-circuit tests. Depending on the design, supervision may include current-sensor plausibility, comparison of independent measurements, analogue-to-digital conversion, controller and memory health, settings integrity, auxiliary supplies, gate-driver health, semiconductor status feedback, trip-path continuity, energy-absorption circuit continuity, cooling, temperature measurement and communications.

5.3.20 The BITE coverage should be assessed against the SSCB failure-mode analysis. It should be clear which failures are detected automatically, how quickly they are detected, the alarm or protective response, and which failures remain dormant until an on-demand test is performed. Particular attention should be given to common dependencies between duplicated channels, including shared current sensors, auxiliary supplies, processors, software, communications, cooling and energy-absorption components. Two channels should not be credited as independent where a single hidden failure can prevent both from performing their required function.

5.3.21 Where the current sensor cannot be exercised by secondary injection, BITE should provide the greatest practicable coverage of the inaccessible measurement chain. Additional confidence may be obtained by reduced-current primary injection, comparison with an independent current measurement during normal operation, sensor plausibility checks, review of manufacturer production-test records, representative type testing and periodic controlled live short-circuit testing. Where the sensor, processing channel and interrupting device form a sealed non-repairable assembly, replacement may be the appropriate response to a failed diagnostic or unexplained measurement discrepancy.

5.3.22 Periodic verification should use the least disruptive test that provides adequate confidence for the attribute being checked, while retaining controlled live short-circuit testing at suitable intervals, or following relevant changes, where this forms part of the approved verification basis. BITE and current-injection tests can normally be performed more frequently and used to detect settings errors, sensor problems, loss of trip-path continuity and degradation of diagnostic coverage. Controlled live short-circuit testing can then reconfirm the complete installed response. Test intervals should account for the consequence of hidden failure, the diagnostic coverage available and the period for which a hidden failure could remain undetected.

5.3.23 Developments in SSCB technology have addressed a long-standing limitation of DC systems, namely the interruption of fault current without a natural current zero. This has made DC power systems more practical for DP vessels.

5.3.24 Rapid interruption or limitation of current can reduce the disturbance and the energy released by a fault. It does not remove arc hazards elsewhere in the installation, or the contribution of other connected sources and stored energy. The claimed benefit should be supported by the device capabilities and the system fault assessment.

5.3.25 Solid-state interruption avoids the contact wear associated with mechanical interruption. The device still depends on semiconductor components, sensing, control power, cooling and energy absorption as applicable. Its ratings, condition, proven fault duty and the OEM maintenance guidance should therefore inform the continuing verification strategy.

5.3.26 SSCBs may be used with mechanical devices in combined or coordinated protection arrangements. The purpose of each device should be clear, whether primary interruption, backup fault clearance or isolation. Where a second device is required as a redundant barrier, its independence and failure coverage should be demonstrated. Two devices in series are not necessarily independent.

5.3.27 Solid-state devices introduce conduction losses and thermal management demands. Some do not provide galvanic isolation and may allow leakage current. The complete arrangement should provide suitable isolation and account for the behaviour of the semiconductor device and any series mechanical device, including a failure to interrupt.

5.3.28 Figures 5-3 and 5-4 illustrate two four-section DC ring arrangements. Figure 5-3 uses bus-tie breakers and a separate AC auxiliary ring, while Figure 5-4 uses solid-state bus-tie devices and distributed energy storage.

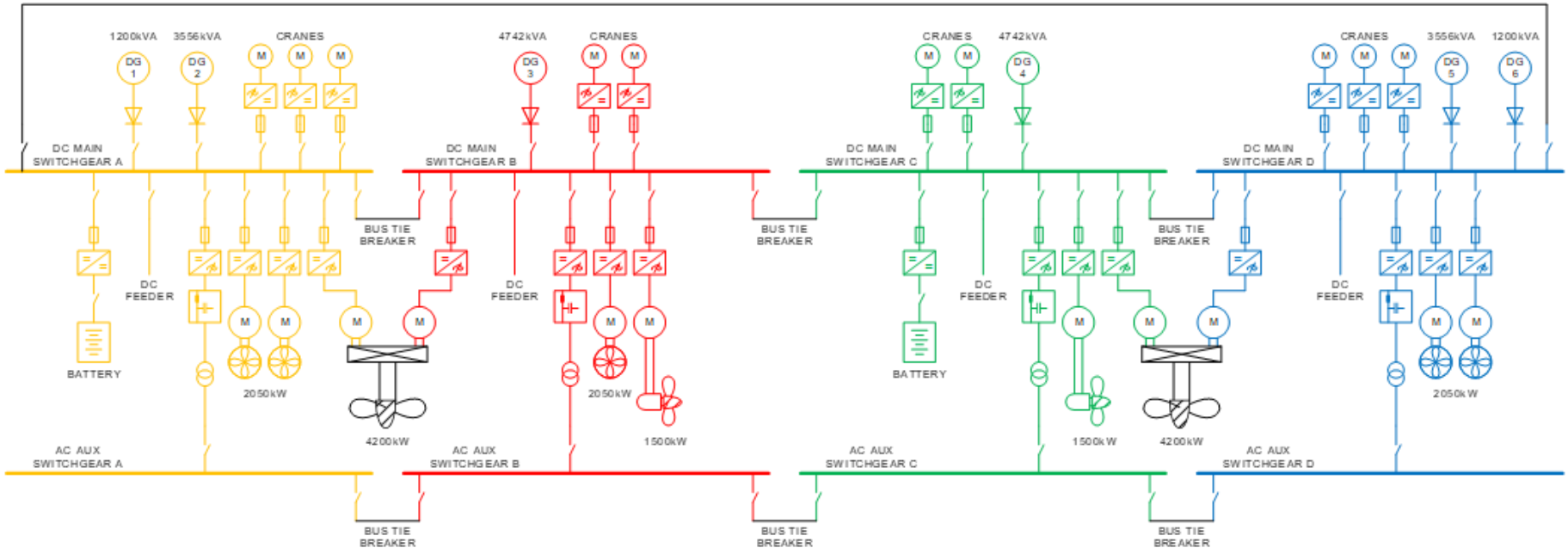


Figure 5-3 DC Topology Example 2, Four-section DC Ring with Bus Tie Breakers and Separate AC Auxiliary Ring

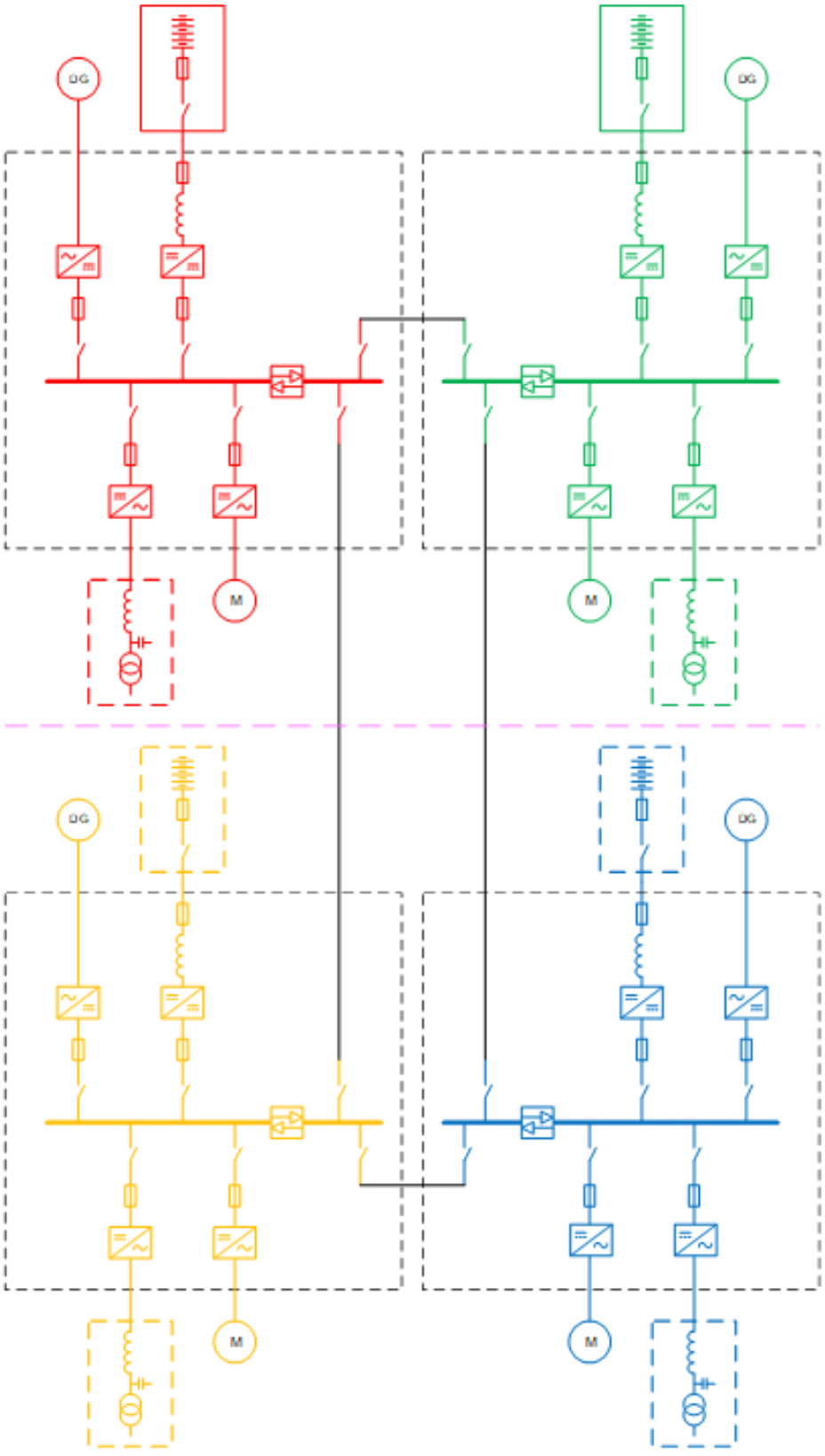
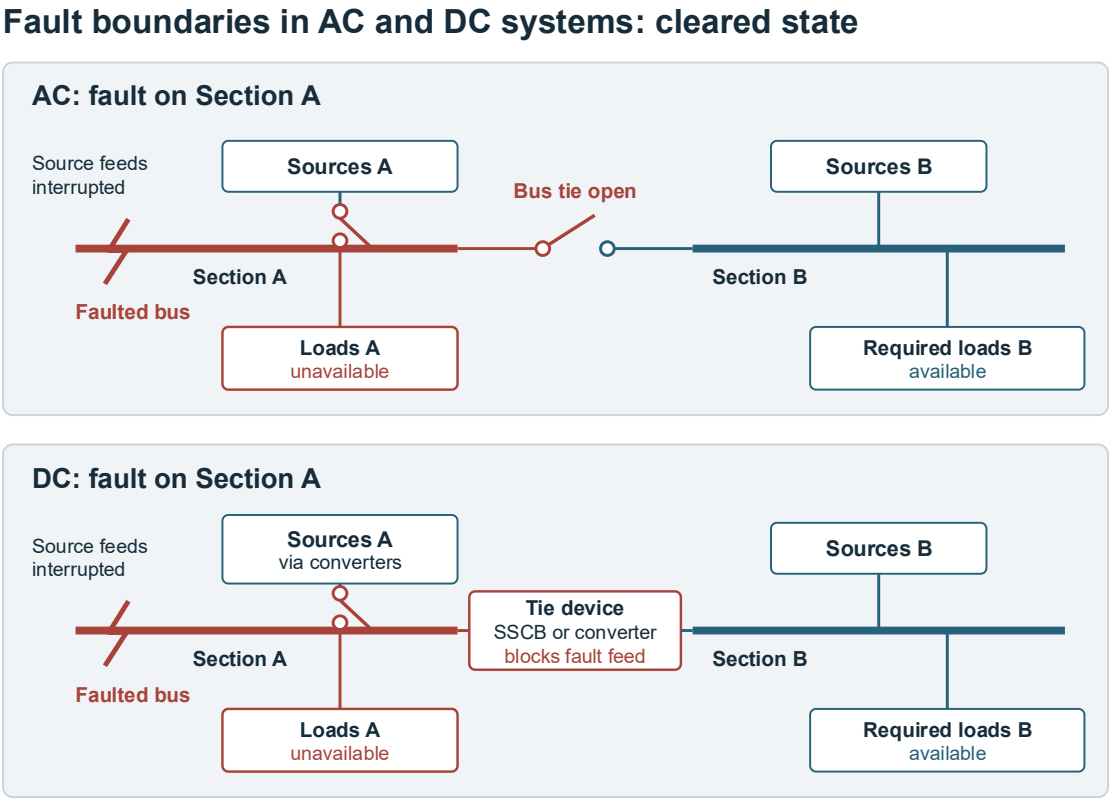


Figure 5-4 **DC Topology Example 3, Four-section DC Ring with Solid-State Bus Tie Devices and Distributed Energy Storage**

5.3.29 Figure 5-5 shows the intended cleared response to a fault on one section. The verification should establish both the complete interruption of the relevant fault contributions and the response of the equipment required to survive, from fault initiation through to recovery.



Before the fault is isolated, Section B equipment is exposed to the disturbance and must ride through it (Section 6.18).

Figure 5-5 Illustrative fault boundaries in interconnected AC and DC systems

6 POWER SYSTEM ATTRIBUTES TO BE VERIFIED

6.1 INTRODUCTION

6.1.1 The purpose of verifying power system attributes is to build confidence that the vessel will respond to the failures considered in the DP FMEA without exceeding the WCFDI. The evidence should explain what is expected to remain available, how the fault is contained and how the surviving system continues to support station keeping.

6.1.2 The attributes below should be considered against the vessel's redundancy concept and intended operating configurations. They are not a list of live tests. Design evidence, equipment information, analysis and testing may be combined, provided the conclusion and the limits of the evidence are clear. Each attribute supports one or more of the four conclusions in Section 4.1.

6.1.3 The attributes address conventional generation, energy storage and the associated conversion and distribution systems. Other energy sources, including fuel cells, should be assessed on the same principles of fault containment, continuity of required functions and support for the surviving redundancy groups. Source specific behaviour should be established from the design and OEM information and should not be assumed to match that of a synchronous generator.

6.1.4 Energy storage systems add complexity to the conventional failure scenarios. Unlike synchronous generators, they are connected through power electronic converters that may respond differently to system disturbances. Bidirectional power flow and fast response introduce further variables into fault conditions, and conventional generator protection schemes may not deal adequately with some converter transient behaviour.

6.1.5 The fuelling and excitation attributes mainly describe AC systems with synchronous generators. Where sources are connected through converters, the assessment should follow the functions the converter actually provides, which may include active power or DC voltage control, current limiting and transitions between operating modes. Reactive power and frequency attributes should not be applied to a DC bus as if it were an AC bus.

6.1.6 **DC POWER SYSTEM LOAD SHARING, SOURCE CONTROL AND APSP**

6.1.7 In a DC power system supplied by AC generators through rectifiers, load sharing between generating sets differs from load sharing between synchronous generators connected to a common AC bus. The DC bus and the conversion equipment decouple the generator electrical frequency and phase from the consumers connected to the DC distribution. The division of responsibility between the engine governor, generator automatic voltage regulator, rectifier controls and higher-level power or energy management functions depends on the rectifier topology and should be established for the installed arrangement.

6.1.8 Where an uncontrolled diode rectifier is used, the rectified DC voltage follows the generator terminal voltage, subject to the rectifier characteristics, generator impedance and load current. The generator automatic voltage regulator therefore has a direct influence on the DC-bus voltage and may establish the voltage-droop characteristic used to share load between sources. The engine governor maintains generator speed and frequency and provides the mechanical torque needed to satisfy the electrical load. The governor does not directly control load sharing on the DC bus in the same way as governors share active power between synchronous generators connected to a common AC bus, but insufficient, excessive or unstable torque can limit or disturb the power delivered through the rectifier.

6.1.9 Where a controlled rectifier, typically a pulse-width-modulated converter, is used, the rectifier controls normally regulate DC voltage, current or power and provide the primary means of load sharing between sources. The engine governor responds to the torque or power demand resulting from the converter controls, while the automatic voltage regulator maintains the generator-side voltage and excitation required for converter operation. The converter can compensate for some variation in generator speed or voltage while operating within its current, voltage and modulation limits. A governor or excitation failure may therefore be partly decoupled from the DC bus or remain initially masked until the generating set or converter reaches an operating limit.

6.1.10 This decoupling can make a DC power system more tolerant of some governor and excitation failures than an AC system in which generators operate directly in parallel on a common bus. A moderate governor failure may not immediately disturb DC-bus load sharing, provided that the engine continues to produce sufficient torque and power to meet the converter demand. Similarly, a controlled rectifier may maintain DC-bus voltage following a moderate change in generator-side voltage. This tolerance should not be interpreted as immunity. The resulting failure may appear later as current limiting, loss of source contribution, unstable power transfer, converter blocking or tripping, engine overspeed, generator overcurrent, or an abrupt transfer of load to the remaining sources.

6.1.11 Where Additional Power Systems Protection (APSP) is provided to detect governor, excitation or source-control failures, its role should be considered against the installed conversion arrangement. Detection based on active-power, reactive-power, frequency or voltage imbalance may behave differently where each generator is connected to the DC bus through a rectifier. The quantities available for identifying the faulty source, and the effect of failing to identify it promptly, depend on whether the rectifier is uncontrolled or actively controlled. The assessment should show that APSP does not incorrectly apply AC-system assumptions to a converter-decoupled DC system and that it distinguishes a generating-set failure from converter current limiting, commanded load transfer and normal control action.

6.1.12 APSP action may be less time-critical for some governor or excitation failures where the converter prevents the initial disturbance from propagating to the DC bus. However, this should be demonstrated for the actual failure and converter operating envelope. Converter decoupling can delay the visible system-level effect and thereby make a developing source failure more difficult to detect. Detection, alarm and protective action should therefore remain effective before the affected source reaches a condition that causes an abrupt loss of power, unstable load sharing or a hazardous voltage excursion.

6.1.13 DC overvoltage is potentially one of the most destructive failure modes in a converter-based DC power system because it can simultaneously expose power-semiconductor devices, DC-link capacitors, converters and energy-storage interfaces to voltage beyond their design limits. A failure of excitation control, rectifier voltage control, regenerative-power control, load sharing or load-rejection response may cause the DC voltage to rise rapidly. Depending on the architecture, connected sources and stored energy may continue to sustain or increase the voltage after the initiating source has been identified.

6.1.14 Overvoltage protection should therefore be treated as a required protection attribute where an overvoltage could cause damage or failure effects exceeding the worst case failure design intent. The assessment should identify the independent means of detecting and limiting DC overvoltage, the devices required to disconnect or suppress the contributing sources, and the total response time. Relevant provisions may include independent voltage measurement, converter blocking, source disconnection, energy absorption, braking resistors, battery charge control and coordinated load or source reduction.

6.1.15 Hidden failure of DC overvoltage protection should be specifically considered. A failed voltage sensor, incorrect scaling, unsuitable threshold, loss of control power, disabled protection function, defective trip path or common software dependency may remain undetected during normal operation. Where practicable, protection should include supervision or periodic verification capable of revealing these conditions. Apparent redundancy should not be credited where multiple protective functions depend on the same voltage measurement, controller, software, control supply, communications path or interrupting device.

6.1.16 Verification should demonstrate both dependability and security. The overvoltage protection should operate before equipment limits are exceeded, but should not unnecessarily remove healthy sources during acceptable transient voltage excursions. The assessment should include the strongest charging or regenerative condition, credible load rejection, failure of the primary DC-voltage controller, loss or saturation of an energy-absorption function, and the applicable backup-protection case.

6.2 FUELLING FAILURE ATTRIBUTES

6.2.1 In a diesel electric system with several generators connected to a common bus (island, closed linear bus or closed ring bus), the first indication of a fuelling failure is usually an imbalance in active power (kW) load sharing. If the fault is severe or progressively worsens, possible outcomes include frequency deviation, reverse power, overload and engine overspeed.

6.2.2 There are many causes of incorrect fuel delivery to an engine, but all fuelling failures fall into one of three categories:

- Under fuelling.
- Over fuelling.
- Unstable fuelling.

6.2.3 In a DC power system supplied by AC generators through rectifiers, a fuelling failure does not directly produce the frequency and active-power-sharing response associated with generators operating on a common AC bus. The DC bus and the intervening rectifiers or converters provide a degree of decoupling between generator speed and the supplied consumers. The generating set may therefore continue to support its assigned DC load following a moderate change in fuel delivery, provided that the engine continues to produce sufficient torque and power to meet the demanded load and the generator and rectifier remain within their operating limits.

6.2.4 The response nevertheless depends on the generator and rectifier arrangement. Under fuelling may cause engine speed, generator frequency and available power to fall until the rectifier reduces or ceases its contribution to the DC bus, or until engine, generator or converter protection operates. Over fuelling may cause overspeed or activate engine control and safety functions, while unstable fuelling may cause oscillation of the available power, DC current or DC voltage. These effects may interact with converter current limits, DC voltage control, energy storage and the load-sharing controls of the other connected sources.

6.2.5 Where variable-speed generating sets or controlled rectifiers are used, load sharing is normally managed through the converter controls by regulating DC voltage, current or power. A fuelling failure may then first appear as an inability of the generating set to follow the power or torque demand commanded by the converter. The validation should establish that the controls identify or accommodate the deficient source without causing unstable load transfer, excessive demand on the remaining sources or loss of the DC bus. The assessment should include failures developing both rapidly and progressively across the intended generator speed and loading range.

6.2.6 On a vessel fitted with an ESS, the analysis should consider both generator fuelling failures and faults that affect the active power or frequency output of the ESS drive. An ESS does not consume fuel directly, but a deviation in its active power output can look very similar to a fuelling fault.

6.2.7 Validation of fuelling and ESS active power failures should demonstrate the following attributes of the detection and protection system:

1. The system correctly identifies the faulty machine across all applicable operating configurations and load levels.

   The number of machines online and the total network load directly affect the system response and the detection strategy. For example, with two engines online at low bus load, an over fuelling machine will produce more power than the healthy machine, and without a suitable identification method the healthy machine may be misdiagnosed as under fuelling. With three engines online at low load, the over fuelling machine is easier to identify because its deviation is much greater than that of the two healthy machines.

2. The system correctly identifies faults that develop at both fast and slow rates.

   Fuelling failures can develop slowly or quickly depending on the mechanism. A clogging fuel filter may cause under fuelling that takes hours to appear and may be missed by an algorithm looking for a high rate of change over a short period. A malfunctioning actuator oscillating at high frequency may escape detection if the sampling rate is too low to capture it. Both cases should be covered by targeted verification and validation.

3. The system has more than one layer of protection, with correct discrimination between them.

   For example, a generator protection device commonly trips its circuit breaker within a set time when specific fault conditions are met. A second layer may open the bus ties in response to a fault originating from another machine, with a longer time delay to give selective isolation.

6.3 EXCITATION FAILURE ATTRIBUTES

6.3.1 The first indication of an excitation failure is usually an imbalance in reactive power (kVAr) load sharing. If the fault is severe or progressive, outcomes may include reverse kVAr, overvoltage, undervoltage, high currents and generator overtemperature.

6.3.2 Excitation failures fall into one of three categories:

- Under excitation.
- Over excitation.
- Unstable excitation.

6.3.3 In a DC power system supplied by AC generators through rectifiers, the effect of an excitation failure depends on the rectifier topology and on which control function regulates the DC bus voltage and source load sharing. The assessment should therefore establish the actual division of responsibility between the generator automatic voltage regulator, the rectifier controls and any higher-level power or energy management function.

6.3.4 Where an uncontrolled diode rectifier is used, the generator terminal voltage directly influences the rectified DC voltage. The automatic voltage regulator may therefore be relied upon to regulate the DC voltage and establish the voltage characteristic used for load sharing between sources. Under excitation may reduce the rectified voltage and cause the affected source to shed load or cease contributing to the DC bus. Over excitation may increase the DC voltage and cause the affected source to take excessive load or expose connected equipment to overvoltage. Unstable excitation may produce oscillation of DC voltage and source current and may interact with the voltage characteristics of the other connected sources.

6.3.5 Where a controlled rectifier, typically a pulse-width-modulated converter, is used, the rectifier controls may regulate DC voltage, current or power and provide the primary means of source load sharing. The generator automatic voltage regulator continues to regulate the generator-side AC voltage or excitation within the capability required by the converter, but its direct influence on DC-bus load sharing may be reduced. An excitation failure may remain partly masked by converter control until the generator voltage or current reaches a converter operating limit, after which the source contribution may reduce abruptly or the converter may block or trip. The analysis should address this transition and show that a failure of either the excitation system or the converter control does not cause unstable power sharing, incorrect identification of the affected source or loss beyond the worst case failure design intent.

6.3.6 The verification should distinguish excitation-system failures from rectifier-control failures that produce similar effects at the DC bus. It should address undervoltage, overvoltage and unstable control, together with current limiting, converter blocking, loss of firing or modulation, control-power failure and transitions between operating modes where these can affect continued operation of the surviving sources.

6.3.7 On vessels fitted with an ESS, the analysis should consider both generator excitation failures and faults that affect the reactive power or voltage output of the ESS drive.

6.3.8 Validation of excitation and ESS reactive power failures should demonstrate the following attributes of the detection and protection system:

1. The system correctly identifies the faulty machine across all applicable operating configurations and load levels.

   The number of machines online and their loading affect the information available to identify the faulty machine. An apparent load sharing imbalance should not cause a healthy generator to be disconnected while the faulty source remains connected. The identification method should be assessed for the intended source combinations, including conditions with only two sources connected.

2. The system correctly identifies faults that develop at both fast and slow rates.

   A slowly developing fault may be missed by an algorithm looking for a high rate of change over a short period. A system that does not sample and react quickly enough may allow voltage to rise beyond the safe limits of the system. Both cases should be covered by targeted verification and validation.

3. The system has more than one layer of protection, with correct discrimination between them.

For example, the excitation limiters in the AVRs may be set so that each alternator absorbs enough reactive power from an over exciting machine for the fault to be detected, without reaching the under excitation trip level of its own protection.

6.4 EARTH FAULT ATTRIBUTES

6.4.1 The earthing arrangement determines the fault paths, the quantities available for detection and the action expected after an earth fault. The assessment should identify the arrangement used for each AC and DC system, including unearthed or insulated arrangements, resistance earthing and any other arrangement relevant to the installation. An earthing transformer is one way of providing an earth connection; the complete protection philosophy also needs to be described.

Note: *There is no restriction in principle on the earthing strategy. In practice most LV AC and DC systems on DP vessels are not intentionally referenced to the hull, the connection being through the insulation impedance and the means provided to detect earth faults. The arrangement installed should be confirmed rather than assumed.*

6.4.2 The objective is to show that earth faults are detected and managed as intended without creating an unacceptable failure path between redundancy groups. Where the design allows continued operation after a first earth fault, the implications of that condition, and of a second earth fault, should be understood. Depending on the system, the expected response may be an alarm, selective isolation or another defined action.

6.4.3 The assessment should include batteries, DC links, converters, filters, insulation monitoring, cable screens and intentional or unintended earth connections where these affect failure propagation. Converter isolation, and the earthing arrangement on each side of it, should be established from the actual design. An ESS should not be excluded on the assumption that it behaves like a generator under earth fault conditions.

6.4.4 The evidence should support the intended detection and isolation functions and the continued availability of the surviving groups. Changes to earth connections, converter arrangements or monitoring equipment should trigger a review of that evidence. The aim is to maintain the earthing and protection philosophy throughout the life of the vessel. Physical application of every possible earth fault is not expected.

6.5 LOAD APPLICATION & REJECTION

6.5.1 Load response tests can establish the attributes of individual generators or ESS. The assessment should also cover the combined response of the connected sources and the effect of power reduction, load shedding and other blackout prevention measures. Satisfactory performance of one source on its own does not establish the response of the complete network.

6.5.2 The following attributes should be validated for load application and rejection:

1. Load reduction response.

   After a credible reduction in available generation or stored energy support, load reduction should act quickly enough and by a large enough amount to prevent further loss beyond the WCFDI. The required response should be established from the intended configuration, the power remaining and the needs of DP critical consumers. A single fixed percentage load step is not a suitable basis for every installation.

2. Load acceptance.

After a credible increase or transfer of load, the surviving sources should accept the demand without unacceptable voltage or frequency excursions, loss of essential consumers or unstable interaction between sources. The load change considered should reflect the vessel's operating limits and the capabilities of the connected generators, converters and ESS. The protection should be able to tell this intended response apart from a fault.

3. Load rejection.

   Loss of significant load can cause a voltage rise and, in AC systems, a frequency excursion. Controls and protection should manage a credible load rejection without unnecessary loss of the equipment required to survive. The response should be established for the connected sources and their operating modes.

4. Protection system integrity.

   Generators and ESS drives are tuned to operate within acceptable limits and may respond slightly differently to changes in system conditions. After a large load change these differences can be amplified and cause generator protection to identify a fault falsely and trip healthy equipment. Protection settings should be validated to show that the protection can distinguish genuine faults from acceptable variations in the response of the generating plant. Quasi-predictive load reduction may also be arranged to shed load in the variable speed drives before a faulty generator is disconnected. Where such a function is required, its response and its interaction with the generator protection should be established.

6.6 UNBALANCED PHASE FAILURE RESPONSE FOR 3 PHASE AC SYSTEMS

6.6.1 Unbalanced phase failures occur only in multiphase networks and usually take one of the following forms:

1. One or two phases open circuit when they should be conducting.
2. One or two phases conducting when they should be open circuit.
3. Unbalanced phase loading caused by faulty three phase machines, or by unbalanced loading of single phase consumers, usually on the secondary side of a power transformer.

Note: *Load current does not flow in a three-phase system when two of the three poles are open, but severe line to earth voltage excursions can occur in some conditions, for example where an earth fault is already present on a generator or on the bus.*

6.6.2 Protection should detect the phase loss or unbalance conditions relevant to the arrangement and distinguish them from acceptable differences in loading. Negative and zero sequence measurements are among the methods used.

6.6.3 The following attributes should be considered when validating a multiphase distribution network:

1. Thermal limit margins.

   The protection should prevent phase unbalance from exposing generators, motors, transformers and converters to duty beyond their limits. For rotating machines, negative sequence heating may be significant. The assessment should relate the size and duration of the unbalance to the equipment limits and to the selective action needed to preserve the surviving redundancy groups.

2. Breaker coordination.

Protection should identify and isolate the faulted part of the network without unnecessary loss of healthy sources or redundancy groups. The sequence of bus tie, feeder and generator actions should follow from the fault location and the protection philosophy. Phase loss, incorrect phase sequence and negative sequence current are different conditions and evidence for one is not evidence for another.

3. Converter and DC link response.

   Supply unbalance increases the ripple on the DC link of rectifiers and active front ends and may operate the DC link under or overvoltage protection, or the input protective devices, at levels of unbalance well below those that threaten a rotating machine thermally. Where thrust is delivered through converters, the converter is often the limiting item. The drive DC bus protection settings referred to in Section 9.3 should be reconciled with the unbalance the system can produce.

4. Detection in single phase and ELV distribution.

   Loss of one phase supplying a transformer, a rectifier or a single-phase distribution may not be detected by protection referred to the three phase system, while still causing loss of supply, or a degraded supply, at the point of use. The means of detecting this condition, and the consequence of not detecting it, should be established for distribution that supplies functions relied upon in the redundancy concept.

5. Back feed following phase loss.

   Loss of a phase on a transformer primary can produce a sustained but reduced and unbalanced voltage on the secondary through the winding connection. This voltage may be high enough to prevent a simple undervoltage relay from operating but too low to support the connected equipment. Where the arrangement allows this condition, the response of the protection and the equipment should be established.

6.7 CURRENT DETECTION

6.7.1 Current detection is an integral part of protection and control. The required functions depend on the accuracy and reliability of the complete sensing path, including the sensor, any signal conditioning, the connecting circuits and the receiving device. Current transformers (CTs) and Rogowski coils are commonly used for AC measurement. DC measurement needs a DC capable sensor, such as a suitable Hall effect sensor or shunt arrangement.

6.7.2 The following attributes should be validated to confirm correct operation of protection and control functions:

1. Ratios, accuracy and errors.

   Protection coordination may be compromised if the ratio, accuracy or error of the current sensing devices is outside the specified limits. This can lead to tripping of healthy systems or failure to trip circuit breakers feeding a fault.

2. Burden capability.

   The connected load and wiring should be compatible with the sensing device and its electronics. For a CT circuit this includes the secondary burden and its effect on accuracy and saturation. For an active sensor or integrator, it includes the power supply, the input and output ranges and the characteristics of the receiving equipment. The same burden criterion does not apply to every sensing technology.

3. Device polarity.

   Devices should be installed with the correct orientation. In zoned or directional protection schemes, a reversed signal can block a legitimate trip or cause the wrong breaker to trip.

4. Secondary circuit terminations.

   Incorrectly terminated secondary circuits are not uncommon, especially where they run across several panels. Incorrect termination of interconnecting wiring can stop protection operating as designed.

5. Measurement range and transient response.

   The sensing path should detect the lowest fault current relevant to the protection function and remain accurate enough at the highest relevant current and during transients. CT saturation, sensor or amplifier limits, power supply behaviour and signal processing should be considered as applicable. The objective is dependable detection and correct discrimination over the whole range on which the redundancy concept relies.

6.8 VOLTAGE DETECTION

6.8.1 Voltage measurement supports protection, control, synchronising and the detection of abnormal system conditions. The functions that depend on it rely on the accuracy and integrity of the complete sensing path, including the voltage transformer (VT) or sensor, its protective devices, the connecting circuits and the receiving device. DC measurement needs an arrangement suited to the signal. Both AC and DC voltages may be measured at more than one point for different purposes.

6.8.2 Loss or corruption of a voltage signal is a credible failure with system level consequences. It is often a hidden failure: the installation continues to operate normally until the affected function is called upon. The following attributes should be validated:

1. Response to loss of voltage signal.

   Failure of a voltage sensing supply, most commonly operation of a VT fuse or miniature circuit breaker, should not cause unnecessary disconnection of healthy equipment or prevent the operation of a protective function relied upon in the redundancy concept. Where VT supervision is fitted, its action on detection (alarm, blocking or change of protection characteristic) should be established, together with the effect of that action on fault clearance.

2. Effect on voltage dependent protection.

   Directional, voltage restrained and voltage dependent overcurrent functions, and any function using a sequence component derived from voltage, should be identified together with their behaviour on loss or corruption of the voltage signal. Where such a function is credited with discriminating a generator or feeder fault in a common power system, loss of its voltage reference is a direct route to a failure effect exceeding the WCFDI and should be addressed in the failure analysis.

3. Effect on synchronising, dead bus detection and blackout detection.

   The voltage inputs used for synchronising, dead bus arbitration and blackout detection should be identified and their failure modes assessed. A single incorrect voltage input should neither falsely initiate nor block these functions. Where blackout detection relies on several inputs (see Section 6.19), the independence of the voltage sensing behind those inputs should be established. Several inputs taken from the same VT circuit or sensing supply are not independent.

4. Scaling, phase association and reference.

Ratio, scaling, phase association, phase rotation and the reference or earthing arrangement of the sensing circuit should be verified in the installed arrangement. An incorrect reference can give a plausible but incorrect reading that a functional check at nominal voltage will not reveal.

5. Measurement range and transient response.

   The sensing path should remain accurate enough over the voltages relevant to the required functions, including the depressed voltage during a fault and the recovery transient. Filtering, sampling and signal processing should be able to represent the transient on which the protection or control decision depends.

6.8.3 The harmonic content of the supply after the loss of a source, transformer winding, filter or converter may take the voltage sensing path outside the range in which its accuracy was established. This should be considered together with Section 6.9 and the current detection attributes in Section 6.7.

6.9 HARMONIC DISTORTION IN AC SYSTEMS

6.9.1 Harmonic distortion should be considered where it can impair a function on which fault ride-through depends. Relevant effects include incorrect sensing, additional heating of equipment, interaction between converters and filters, failure to synchronise, and loss of a control or auxiliary supply. The concern is the effect on the installed system, as well as whether the measured distortion is within its applicable limit.

6.9.2 The evidence should cover the configurations in which the power system is expected to operate during and after a fault. Loss of a generator, transformer winding, filter or converter can change the harmonic content seen by the surviving system. Measurements taken in normal operation may not represent those conditions.

6.9.3 Post fault harmonic content is of particular concern for protection. It can move CT, VT and relay measurement outside the range assumed in the protection coordination study at the time the surviving group depends on that protection. The measurement range attributes in Sections 6.7 and 6.8 should therefore take account of the post fault harmonic environment.

6.9.4 Calculations, OEM information and measurements may be combined to show that the affected equipment continues to perform its required function. Later changes to source combinations, converters or filters should be reviewed against this basis. Detailed harmonic limits and the method of verification should be chosen to suit the installation and its applicable requirements.

Note: *Harmonic studies should consider the worst case failure of the harmonic cancellation and filtering functions themselves, and not only the worst case failure of the power system. Loss of a filter, of a phase shifting transformer winding or of a converter control function can change the harmonic environment more than the loss of a generator.*

6.10 COMMON MODE FAILURES OF DC SYSTEMS

6.10.1 Failures able to affect more than one redundancy group through a shared dependency are addressed generally in TECHOP G-02 and by the C^3EI^2 method in TECHOP D-01. This section applies those methods to DC systems and to the supplies, returns, earthing, controls, communications and cooling associated with them.

6.10.2 Groups connected through a divided bus or a converter may still share dependencies. The intended barriers to fault propagation should be identified and supported by evidence.

6.10.3 The assessment should cover relevant pole to pole and pole to earth faults, unintended return paths and earth loops. It should also consider disturbances associated with switching, voltage variation, ripple and the failure of capacitors or filters.

Note: *Common mode voltage and common mode failure are different things: the first is an electrical condition, the second is loss of more than one required function through a shared vulnerability. However, common mode voltage can be the cause of a common mode failure.*

6.10.4 The source of the fault current and its path should be understood. Batteries, capacitors, rotating machines and converters contribute differently, and current may flow in more than one direction. Converter current limiting or blocking should not be taken as proof that every fault path is interrupted. The response during a converter failure, a change of operating mode or the use of a bypass should be considered where it could defeat the intended barrier.

6.10.5 Control and auxiliary supplies are part of this assessment. For example, a fault on one 24 V DC branch may pull down a common supply if the source cannot operate the branch protection selectively. Dual feeds may also provide an unintended back feed path. The evidence should show that the fault is contained and that the healthy functions remain available at their points of use. UPS arrangements are addressed in Section 6.11 and discrimination in final distribution in Section 6.12.

6.10.6 The basis of confidence should identify the functions that provide separation, how failure of those functions is detected and what checks are needed to keep them effective. Changes to converters, protection, shared services, wiring or software should be assessed for their effect on the established boundaries.

6.11 UNINTERRUPTIBLE POWER SUPPLIES AND CONTROL POWER

6.11.1 Uninterruptible power supplies (UPS) commonly support the DP control system, position reference systems, protection control power and other functions intended to remain available through a disturbance. The fault and disturbance behaviour of a UPS depends on the state in which it is operating, and a demonstration in one state does not cover another. The following attributes should be validated for each state that may be in use:

1. Fault clearing capability in each defined operational state.

   The fault current available at the output should be established for normal operation, for operation from stored energy and for bypass, and compared with the operating characteristic of the downstream protective devices. An inverter may current limit below the pickup of a branch device, so that a fault on one outgoing circuit is not cleared while the unit is running on its inverter, although the same fault would be cleared on bypass. Where this is possible, the consequence for the healthy circuits on the same distribution should be assessed (see Section 6.12).

2. Transfer behaviour.

   The transfer time between supply states, and any interruption or voltage excursion during transfer, should be established and compared with the immunity of the connected equipment at its terminals. Transfers caused by a disturbance on the incoming supply, by a fault on the output and by an internal failure should each be considered.

3. Indication and supervision of operating state.

   The operating state should be indicated, and alarmed where a change of state affects a required attribute. Continued operation on bypass, or with the battery unavailable, removes the protection the UPS was expected to provide and should not go unnoticed.

4. Stored energy capability and duration.

The available stored energy should support the required function for the required period, taking into account the redundancy concept and, where relevant, the time needed to terminate the activity safely. State of charge, state of health, temperature and age affect this capability. The means of maintaining and checking it should be identified.

5. Input and distribution arrangement.

   The incoming supplies, their origin in relation to the redundancy groups, and any alternative or dual feed arrangement should be established, together with any potential back feed path or unintended common point between groups. A dual fed arrangement is a cross connection and should be analysed as such.

6.11.2 The same principles apply to other control power arrangements, including DC distribution supplied from batteries and chargers, and control power supplied through converters. In each case the attribute of interest is that a fault is contained and that the healthy functions remain available at their points of use.

6.12 DISCRIMINATION IN FINAL DISTRIBUTION

6.12.1 The supplies to DP critical equipment usually end in distribution protected by fuses or by miniature or moulded case circuit breakers (MCBs or MCCBs). At this level, discrimination between a branch device and the device upstream of it depends on the energy let-through during the fault, and backup or cascade protection may be relied on at higher fault levels. The behaviour of this protection decides whether a fault on one branch stays within that branch or causes a loss of supply to the healthy branches on the same distribution.

6.12.2 The following attributes should be validated:

1. Selectivity at the relevant fault levels.

   Discrimination between the branch device and the upstream device should be established across the range of prospective fault current at the point of installation, including the lowest current that a current limited source, converter, inverter or battery arrangement can deliver. Selectivity at the maximum prospective fault current does not demonstrate selectivity at a lower current, and the reverse also applies.

2. Validity of manufacturers' discrimination data.

   Where selectivity is taken from published discrimination tables, the device pairing, the ratings and the prospective fault current for which the data is valid should be recorded. The data applies only to the stated combination. Replacing a device with one of the same rating but from a different range or with a different characteristic can invalidate the selectivity without any visible change to the installation.

3. Behaviour of the source during a branch fault.

   Where the source goes into current limit before the branch device operates, the fault may not be cleared and the voltage on the healthy branches may remain depressed. The source behaviour, the branch device characteristic and the tolerance of the equipment on the healthy branches should be assessed together. This applies to current limited DC supplies, to inverter supplied distribution and to supplies taken through a converter.

4. Control of change.

The devices, their characteristics and the basis on which selectivity was established should be recorded so that any later substitution can be assessed. Additional loads connected to an existing distribution, and cross connections added for convenience, should be assessed for their effect on selectivity and on the independence of and separation between redundancy groups.

6.12.3 Section 16.2 gives an example of this mechanism on a 24 V DC control distribution. The same principles apply at 230 V AC and at other final distribution levels, including distribution supplied from a UPS.

6.13 INTEGRATED SETTINGS (FOR ALL PROTECTION DEVICES)

6.13.1 TECHOP D-04 gives guidance on the evaluation and classification of protective functions, including the consequences of combining protection and control functions in the same device. That guidance applies to protective functions in converters, drives, the power management system, the vessel management system and other parts of the integrated automation system considered in this section and in Sections 6.14 and 6.16.

6.13.2 Settings should be treated as part of the redundancy concept. The required response may depend on coordinated functions in protection relays, circuit breakers, converters, generators, ESS, auxiliary supplies and control systems. Each device can be correctly set while the overall sequence is still wrong.

6.13.3 The approved or otherwise authorised settings should be traceable to the relevant studies and operating configurations. The record should identify the functions, devices and software versions to which it applies, including relevant internal limits and restart or recovery settings, in enough detail to show that the installed arrangement matches the arrangement assessed.

6.13.4 Commissioning, maintenance and modification should preserve this relationship. Where settings are changed temporarily for testing, the effect on the evidence and the means of confirming that the original settings have been restored should be clear. A later change should be assessed against the affected protection, performance and detection attributes before earlier results are relied upon.

6.14 RELAY & PROTECTIVE DEVICE RESPONSE

6.14.1 The protection response should be considered as a complete chain from detection to effective isolation of the fault. Depending on the arrangement, the chain may include sensors, logic, communications, operating power, trip circuits and interrupting devices. The evidence should show that the required action takes place within the time and duty assumed in the redundancy concept.

6.14.2 Both dependability and security should be addressed. The protection should operate when required and should not operate unnecessarily and remove healthy sources or consumers. Where backup or independent protection is required, its ability to act after failure of the primary function should be supported, including the dependencies the two have in common.

6.14.3 Relay operation, operation of the installed trip path, mechanical opening of the contacts and interruption of the fault current are related but separate attributes, and the evidence should distinguish between them. No-load operation or signal injection can provide valuable evidence, but does not demonstrate the full interrupting duty.

6.14.4 Continuing verification should address the parts of the chain whose effectiveness can change through use, ageing, maintenance or modification. Suitable diagnostics and condition information may reduce the need to repeat intrusive tests, provided they cover the failure mechanisms relevant to the function.

6.15 ARC FAULT DETECTION

6.15.1 An arcing fault in LV switchgear may produce a fault current well below the prospective bolted fault current at the same point. It may therefore be below the pickup of the overcurrent protection credited with isolating it, or be cleared only after a delay set by an inverse time characteristic. Where the redundancy concept relies on such a fault being contained within one section, the means of detecting it is a required attribute and should be verified as such.

6.15.2 Where an arc detection system is fitted, the following attributes should be validated:

1. Zone of coverage.

   The physical extent of the detection should be established, including the cubicles, compartments and busbar sections covered and those that are not. The relationship between the detection zone and the boundary required in the redundancy concept should be explicit. A fault in an uncovered compartment falls back on the conventional protection and its clearance times.

2. Detection principle and its dependencies.

   The detection principle should be identified (commonly light detection with or without a current check, pressure detection, or a combination), together with the sensors, control power, processing and outputs on which it depends. Where a current check is used, the arcing fault current should be shown to satisfy it, including with the source combinations that give the lowest fault contribution.

3. Self-supervision and failure response.

   The means of revealing loss or degradation of the detection function should be established, including sensor supervision, control power monitoring and the response to a failed sensor. The consequence of an undetected loss of the function should be assessed against the WCFDI, since its absence is not apparent in normal operation.

4. Coordination and the interrupting path.

   The device or devices tripped by the arc detection system should be identified, together with the total time from detection to interruption and the coordination with the conventional protection. Where an upstream device is tripped, the resulting loss of healthy equipment should be established and reconciled with the redundancy concept.

5. Security.

   The system should not operate on light or pressure from a source other than an arcing fault where this would remove healthy equipment. The measures relied on to achieve this, including current checks and sensor placement, should be identified.

   Note: *Arc detection (optical or pressure) is occasionally used as backup protection to a conventional overcurrent protection scheme. It is not tested during live short circuit testing and therefore other means to develop confidence in this type of protection is required such as those described below.*

6.15.3 A functional test using a light source or signal injection at the sensor shows that the detection, logic and trip path within the test boundary work. It does not show that an arc will be detected under fault conditions, that the current check is adequate at the lowest relevant fault contribution, or that the arcing fault current will be interrupted. The conclusions supported by the chosen method, and those left to other evidence, should be identified as described in Section 12.

6.16 COMPREHENSIVE PROTECTION CO-ORDINATION STUDY

6.16.1 The protection coordination study should establish how faults are detected and isolated while preserving the required healthy parts of the power system. Its scope should follow the DP FMEA and the intended configurations, including the cross connections and supporting supplies through which a failure could affect more than one redundancy group.

6.16.2 In this TECHOP, the protection scheme includes all protective and control functions capable of influencing the detection, containment or consequences of a power-system failure, including functions within protection relays, circuit breakers, converters, drives, generating sets, energy-storage systems, power management systems, vessel management systems and other functions within the integrated automation system.

Note: *It is of paramount importance the DP system FMEA consider a comprehensive range of power system failures and that the coordination study (and computer simulations where required) considers all those power system failure modes identified in the FMEA.*

6.16.3 The study should consider the available fault current over the relevant range of source combinations and operating conditions. The highest current matters for equipment duty; a lower or current limited contribution may be more demanding for reliable detection and prompt clearance. AC and DC source behaviour, stored energy, current direction and converter operating modes should be represented where they affect the result.

6.16.4 The study should also account for protective and control functions outside the main switchboard that can influence the outcome. These may include drive limits, generator safety functions, source current limiting, load reduction, auxiliary protection, arc protection and control power distribution. The objective is a coordinated system response. A set of individually acceptable settings does not guarantee one.

6.16.5 The study should identify the isolation sequence, the disturbance imposed on healthy equipment, the backup response and the remaining system capability. Uncertainties should be stated. The installed settings and equipment should be reconciled with the study, and significant changes should lead to a review of the affected conclusions.

6.17 CONTACTOR AND RELAY RIDE-THROUGH AND MOTOR RE-ACCELERATION

6.17.1 Electromechanically held contactors and relays drop out when the voltage at the coil falls below the drop out level for longer than the release time. On LV installations these thresholds are commonly reached during a correctly cleared fault, at a voltage and for a duration that the generators, converters and drives on the same system can tolerate. The power circuit rides through while the auxiliary and control circuits do not, and the required function is lost as a consequence of the electrical event but may only be evident after a delay. Verification and validation activities should take the above into consideration.

6.17.2 The following attributes should be validated:

1. Identification of dependent loads.

   The DP critical functions that depend on an electromechanically held contactor, relay, starter or interposing device should be identified. These commonly include thruster and generator cooling and lubrication, ventilation and fan starters, fuel and pre-lubrication pumps, and interposing relays in control and protection circuits. The identification should follow the functional dependencies of the required surviving function and not only the main single line diagram.

2. Drop out threshold and time against the disturbance envelope.

For each such device, the drop out voltage and release time should be taken from equipment data and compared with the disturbance envelope at the coil supply. The coil supply may be at a different voltage level, and behind conversion or stored energy support. The comparison should use the complete clearance time, including the applicable protection failure case, and not the relay setting alone.

3. Consequence of drop out.

   Where drop out occurs, the consequence should be established: whether the load restarts automatically, whether a local reset or control system action is needed, whether an interlock or safety shutdown latches, and for how long the affected function is unavailable. The effect on the local subsystem, running generators, thrusters, position and heading should be stated against the WCFDI. A function that recovers automatically after an interval is not equivalent to one that was maintained, unless the acceptance criteria say so.

4. Re-acceleration of the surviving motor group.

   Where motors remain connected during the disturbance, their combined re-acceleration current should be assessed for its effect on the surviving power system. Motors that disconnect and reconnect automatically may add further starting or accelerating current. Depending on the timing, source capability and system response, the combined current demand may delay voltage recovery, prolong the voltage depression or cause a further voltage dip after fault clearance. It may also operate overcurrent protection or cause current-limited sources and converters to limit, block or trip.

   The assessment should establish whether the resulting voltage and current profile could cause additional contactor drop out, loss of healthy consumers, operation of feeder or source protection, failure of auxiliaries to restart, or delay in the recovery of required DP functions. The protection assessment should distinguish motor re-acceleration and restarting current from a continuing or new fault so that equipment intended to survive is not unnecessarily disconnected.

   Where sequenced or staged restarting is relied upon to limit the combined current demand, the sequencing function is a required attribute of the redundancy concept. Its operation, timing, dependencies and relevant failure modes should therefore be verified.

   Note: *Where directional overcurrent protection is used, the assessment should confirm that the protection can distinguish the current associated with a continuing fault from the current associated with motor re-acceleration after fault clearance. Voltage recovery, current direction, timing and other available quantities may be used to support this discrimination.*

5. Mitigations.

   Where a mitigation is relied upon, the evidence should show that it is effective in the installed arrangement and identify the conditions it depends on. Common mitigations include ride-through modules and other stored energy at the coil supply, electronically controlled or DC held contactors, mechanically latched devices, and undervoltage relay time delays coordinated with the clearance envelope. Each introduces its own dependencies, such as a supply, a stored energy element or a semiconductor, which should be identified and maintained.

6.17.3 Verification of this attribute does not necessarily require a fault to be applied. A controlled voltage disturbance at the relevant supply, applied as described in Section 12 and measured at the coil, may provide the evidence needed, provided the applied disturbance is shown to be relevant to the envelope derived for that point of use.

6.18 FAULT RIDE-THROUGH (SHORT CIRCUIT RIDE-THROUGH)

6.18.1 Fault ride-through should be demonstrated for the functions that must remain available while a fault is detected and isolated and the surviving system settles. The assessment should link the electrical disturbance to its effect on power, thrust, control and station keeping. A consumer that stays energised, or a drive that does not trip, has not necessarily maintained its required function.

6.18.2 The disturbance should be described at the point of use. This includes the depth and duration of any voltage dip or interruption, the voltage recovery and any subsequent swell or instability. Frequency, phase unbalance and phase displacement may be relevant in AC systems. In DC systems, source current limits, stored energy and converter behaviour may determine the disturbance and the recovery. A generic waveform will rarely represent a particular arrangement. Section 16.5 gives an example of deriving a disturbance envelope.

6.18.3 The equipment response should include the supporting services on which the function depends. For a thruster these may include control power, communication, contactors, cooling, lubrication and the drive itself (see Section 6.17). Intended ride-through provisions such as stored energy, kinetic buffering or dynamic braking should be assessed together with their limits and their effect on available thrust. Relying on these provisions is acceptable where their limits are understood.

6.18.4 The evidence should address each of the four conclusions in Section 4.1. No single method necessarily demonstrates all four, and the contribution and limitation of each study, equipment record and test should be clear.

6.18.5 The conclusion should state the effects on the local subsystem, running generators, thrusters, position and heading, in relation to the WCFDI. The required surviving functions and the acceptable transient response should be established for the vessel and its intended activity. Recovery of a function after a trip should not be presented as continuous ride-through unless the agreed acceptance basis allows for it.

6.18.6 The basis of confidence should stay linked to the installed configuration, settings, software, source capability and equipment condition. The evidence should be reviewed when any of these change, or when faults or operating experience call the expected response into question. Sections 7 to 14 describe how suitable methods and continuing verification support this.

6.19 BLACKOUT RECOVERY

6.19.1 TECHOP D-03 provides the primary guidance on blackout recovery and should be applied in full. This section addresses the additional points that arise where the recovery arrangement is interconnected, converter based or dependent on stored energy.

6.19.2 Blackout recovery is the last line of defence of the vessel’s power generation and distribution system. Loss of power for propulsion and station keeping is a significant risk to life, property and the environment. Reliable blackout detection and recovery are needed for both open and closed bus configurations because:

- Essential attributes such as performance, protection and detection can degrade over time and be present as a pre-existing condition when another fault occurs. The primary means of detecting such hidden failures is periodic testing and so it is possible the DP system is in an unknown degraded condition at the time another fault occurs.

- Even a system that has passed a rigorous verification and validation programme retains a small probability of a fault that exceeds the WCFDI.
- Increasing complexity and interdependency in power systems, particularly involving software, firmware and digital networks, introduces failure modes that cannot all be anticipated or validated.

6.19.3 Progressive insights from incidents have shown the value of independent recovery arrangements when several defences have been defeated or an unanticipated failure has occurred.

6.19.4 Blackout recovery is distinct from fault ride-through. It provides a further defence after loss of supply. Successful recovery does not show that the functions intended to ride through a fault remained available.

6.19.5 The following attributes should be considered when establishing the recovery arrangements:

1. Independent isolation for recovery.

   A fault in one redundancy group should not prevent recovery of another. Where interconnected groups have to be separated, the means of separation should remain available after the failures considered in the recovery philosophy, and dependence on common control, sensing or operating power should be addressed. In some arrangements a local breaker trip provides this function; converter based and other arrangements should show how the same outcome is achieved in their design.

2. Blackout detection security.

   Failure of, or an incorrect input from, a single blackout detection sensor should neither falsely trigger nor block blackout recovery. Several independent inputs should be used to detect a blackout (see also Section 6.8). It is recommended that an alarm warns the operators of a signal mismatch or sensor failure on the inputs used for blackout detection.

3. Independent recovery of redundancy groups.

   Each redundancy group should be able to detect a blackout and start recovery without relying on another group that may have failed. Shared signals or supporting services should not allow a failure in one group to prevent recovery of another.

4. Restart of auxiliary systems.

   Recovery sequences should give priority to restarting auxiliary systems essential to station keeping, such as cooling and lubrication for generators and thrusters.

5. Thrusters ready for DP without local intervention.

   Thrusters should become available at the DP control station without a manual reset at the local drive or thruster control panel, unless a fault required a safety shutdown. The handshakes between the blackout recovery system and the thruster controllers should be timed so that reset and start request signals do not prevent a restart or lock out a thruster.

6. Staged restart to prevent overload.

   The restart sequence should prevent overload and excessive starting or inrush current from defeating recovery. Failure of a function that limits starting current should be considered where it could affect the outcome. For example, a transformer arrangement may allow connection with fewer generators only when its pre-magnetisation function has operated correctly.

7 PRACTICAL CONSIDERATIONS

7.1 SAFETY

7.1.1 Where testing is used, it should build confidence in the design without creating unjustified risk to people, the vessel or its equipment. The choice of method should take account of the consequences of the intended test and of a more severe or unexpected outcome. Low voltage does not mean low fault energy or low test impact.

7.1.2 The test programme should be developed within the vessel owner's safety management system, with technical input from the relevant OEMs and other stakeholders. The operating condition and location should be suitable for a possible loss of power, thrust, control, position references and mission equipment. An intrusive test should not rely on the industrial activity remaining unaffected.

7.1.3 Before testing, there should be confidence in the condition of the equipment, the proposed test duty, the relevant protection and the means of recording the result. Temporary supplies, connections, settings and test interfaces should be assessed, as they can introduce failure paths that do not exist in normal operation. The programme should state the conditions under which testing is to stop or be held, who has that authority, and how the vessel and equipment will be returned to a known condition.

7.1.4 Restoration should be planned as part of the test. It should cover removal of temporary changes, confirmation of the intended settings and interlocks, any required inspections, replenishment of stored energy and confirmation of the operating configuration. Return to service should follow the vessel's authorised process, taking account of unresolved findings and restrictions.

7.2 STAKEHOLDER RESPONSIBILITIES AND COMMUNICATION

7.2.1 Responsibilities should be agreed before the verification programme is finalised. A RACI matrix, or another clear record, may be used to show who is responsible for the work, who is accountable for each decision, and who should be consulted and informed. Any such record should reflect the actual authority and interfaces of the parties involved.

7.2.2 The allocation should cover at least the following:

- The assurance objective and the evidence required.
- Selection of methods, and the applicable requirements.
- Suitability of the equipment for the proposed method.
- Vessel readiness, and the authority to proceed and to stop.
- Execution, data collection and review of the results.
- Disposition of unexpected results.
- Restoration and return to service.

7.2.3 Where separate suppliers provide equipment, protection, controls or supporting services, the owner of each interface should be identified. Where a DP system integration (DPSI) process is applied as described in JDP01, it provides a means of coordinating these interfaces.

7.2.4 The agreed programme should give the vessel team and the technical stakeholders a common understanding of the expected result, the limits of each method and the evidence needed to reach a conclusion. Changes during the work should be communicated to those whose decisions or evidence are affected. Witnessing a test is not the same as accepting its technical conclusions or authorising return to service. Section 16.8 lists the contributions typically made by each stakeholder.

7.3 EXPERTISE REQUIREMENTS

7.3.1 The competence required depends on the system and on the question being answered. The team should collectively understand the power system design, its protection and controls, the proposed methods, the equipment limits and the DP redundancy concept. LV DC and converter based systems may need expertise beyond that used for conventional AC protection.

7.3.2 Those selecting and interpreting the evidence should be able to explain how a local electrical response affects the vessel. Equipment knowledge, modelling capability and practical testing experience complement each other. Where there is a significant gap in competence, specialist support should be obtained before conclusions are drawn or tests are undertaken.

7.4 MANAGEMENT OF CHANGE

7.4.1 The basis of confidence should be maintained through the vessel's management of change process. A change may affect fault ride-through even when the main single line diagram is unchanged. Relevant changes include settings, firmware, control logic, protection, earthing, source capability, energy storage, supporting supplies, shared services, protective device substitutions and operating configurations.

7.4.2 The review should identify which attributes and earlier conclusions are affected, what evidence remains valid and what further verification is needed. Any retesting should be directed at the affected conclusions and their interfaces. Repeating the whole original programme without this review adds burden and may still miss the effect of the change.

7.4.3 The resulting configuration, settings, evidence and operating limitations should be recorded so that future operators and assurance providers can understand the current basis. Temporary changes made for testing should be managed in the same way and closed out when the intended configuration is restored.

7.5 NEWBUILD vs VESSELS IN SERVICE

7.5.1 A newbuild provides the opportunity to make the required attributes easy to verify. The design should provide access to relevant measurements, clear identification of settings and equipment, suitable test interfaces and separation of fault paths. These provisions should be considered together with the expected verification and maintenance burden over the life of the vessel.

7.5.2 For a vessel in service, the available design, factory, commissioning and service evidence should be reviewed before any additional testing is specified. Where that evidence can be traced to the installed arrangement and remains valid, it can reduce the scope of new work. Missing records should be recorded as an evidence gap. Satisfactory service history does not demonstrate behaviour under a fault condition that has never occurred.

7.5.3 Test provisions or modifications retrofitted to improve ride-through should be assessed for their effect on the existing redundancy concept. The aim is a proportionate route to defensible evidence, taking account of equipment condition, access and operational constraints.

7.6 BURDEN AND IMPACT OF VERIFICATION

7.6.1 The verification and validation burden includes preparation, technical support, equipment access, temporary changes, data collection, interpretation, vessel availability and restoration. It also includes any wear, maintenance or loss of equipment capability caused by a test. These should be considered when selecting the evidence needed to build confidence.

7.6.2 The duty imposed by a test should be understood in relation to the installed equipment, its condition and its previous service. Making, carrying and interrupting a fault impose different duties. Switching an unloaded circuit, injecting current at a test voltage and interrupting a live fault are not equivalent events. Component ratings and factory type tests are not permission for an unlimited number of fault operations in service.

7.6.3 Existing evidence should be used where its identity, relevance and continuing validity can be established. Representative testing and validated models can reduce unnecessary repetition where they show why untested items or configurations are covered. Installation specific matters such as wiring, settings, polarity and trip paths still need appropriate evidence.

7.6.4 The programme should select the least intrusive combination of methods that adequately supports the required conclusions and meets the applicable requirements. A method with lower impact may leave part of a conclusion unproven. That limitation should be recorded and addressed by other evidence, and the method should not be described as equivalent to one that would have proven the conclusion.

7.6.5 An unexpected result should be investigated before an intrusive or high energy event is repeated. Controlled diagnostic work may be necessary, but repeated application of a fault should not be the main means of finding out why the system failed. The cause, the equipment condition and the implications for earlier results should inform the next step.

7.6.6 Continuing verification should concentrate on the attributes that can deteriorate or change, and on the conditions that would invalidate existing evidence. Periodic checks, maintenance, diagnostics, event review and targeted tests each contribute in different ways. Automatic repetition of the original high energy test is not a sufficient basis on its own, and neither is a blanket exemption from further testing.

7.6.7 JDP01 grades verification activities by burden and application (see Section 4.3). The selection described here is intended to be consistent with that grading.

7.6.8 Figure 7-1 summarises the selection of proportionate verification. Applicable Class, statutory and contractual requirements still govern. Where the evidence shows that an attribute is deficient, investigation and corrective action are needed; further testing will not resolve the deficiency.

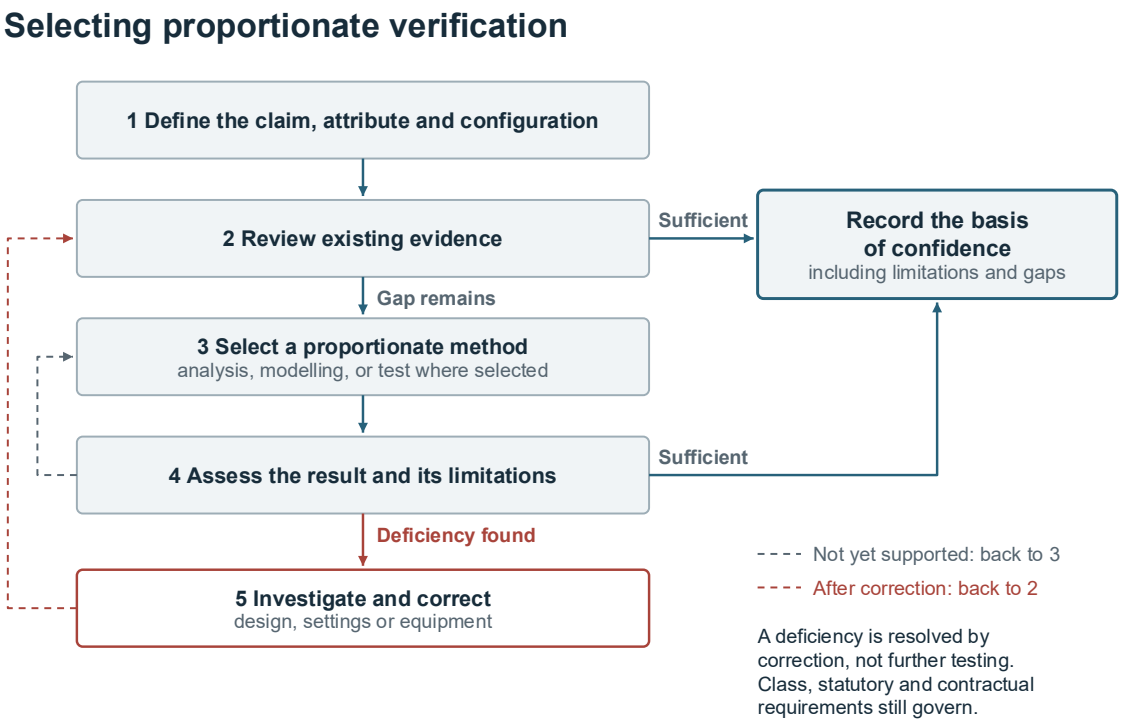


Figure 7-1 Selecting proportionate verification to address the remaining gap

8 MODELLING & CALCULATIONS

8.1 INTRODUCTION

8.1.1 Mathematical modelling of marine power systems, using OEM proprietary or commercially available simulation software, is now well established as a means of predicting the effects of power system faults. Standard models of protective functions are widely available, and bespoke protective functions can be modelled and integrated.

8.1.2 Simulation is increasingly used to supplement live testing and is required by several Classification Society notations for DP vessels operating with closed bus ties or other forms of power transfer between redundant DP equipment groups. Examples include the applicable provisions of DNV-RU-SHIP Pt.6 Ch.3 Sec.1 and Sec.2.

8.1.3 DP notations may also specify:

- The accuracy with which the simulation must reproduce the results of live testing, as a means of validating the model.
- The types of fault that must be modelled, such as intermittent and arcing faults.

8.1.4 The modelling approach should suit the question being answered and the applicable requirements. Detailed time domain simulation is valuable where dynamic interactions decide the outcome. For simpler arrangements, suitable calculations and established equipment information may be enough. The level of modelling should be justified by the uncertainty it resolves.

8.1.5 Where time domain modelling is used, results may be presented as voltage and current waveforms showing fault initiation, protective actions and system recovery. The scope should include the primary and backup protection responses on which the assessment relies.

8.1.6 The modelling report should include a narrative describing the methods used to build the model and any areas of uncertainty. It should state whether the protection coordination study is confirmed as valid and effective. Conclusions and graded findings should identify any non-compliance with the specified acceptance criteria.

8.1.7 The modelling scope should follow the failure effects identified in the DP FMEA, including propagation through closed bus ties, converters and other cross connections. It should not be limited to faults for which a relay setting has already been specified. Where a relevant effect is outside the scope of the model, the report should identify the other evidence used to address it.

8.1.8 The model should help explain both fault isolation and the response of the required surviving functions. Agreement with the protection coordination study is useful but does not establish the fault ride-through capability of the installed system.

8.1.9 Some DP notations require the protection coordination study, and therefore the model, to consider all protective functions capable of influencing power system failure effects. These include functions within variable speed drives, the PMS, the VMS, other relevant parts of the IAS, engine control and safety systems, and the DP control system. Examples are engine mechanical overspeed protection and thruster drive kinetic buffering.

8.1.10 Confidence in a model depends on its suitability for the behaviour being assessed, the quality of its input data and its comparison with relevant measurements. The report should identify the configuration and equipment represented, the important assumptions, the areas of uncertainty and the range over which the model has been validated. Agreement with one recorded event does not validate the model for every operating mode or fault type.

8.1.11 Where model results are used to support configurations that have not been tested, the basis for doing so should be explained. The assessment should consider whether differences in source state, loading, control mode, protection or stored energy introduce behaviour not covered by the validation evidence. Significant differences between prediction and measurement should be resolved before the affected conclusions are relied upon.

8.1.12 The model and its supporting evidence should remain traceable to the installation. Changes to equipment, settings, software or operating limits should be reviewed for their effect on model validity, so that the model remains a useful engineering tool through the life of the vessel and any further modelling or testing is directed at the conclusions that have changed.

8.2 EXPERTISE REQUIREMENTS

8.2.1 Marine power systems differ from their shore-based equivalents in ways that affect how models are built and solved:

- There are generally no transmission lines in marine power systems, although this may change with the adoption of floating charging facilities and shore power connections.
- Marine power systems are compact, closely coupled and isolated, which makes them susceptible to significant voltage and frequency variations.
- Generator fuel and excitation controllers play a larger part in predicting the outcome of faults, which can require bespoke modules to be developed.

8.2.2 Expertise requirements for mathematical modelling of marine power systems include:

- Appropriate academic qualifications and practical knowledge of marine power systems.
- Experience of building mathematical models of marine power systems for DP vessels.
- Experience of validating models against measured system behaviour, and an understanding of the limits of that comparison.
- Familiarity with the practical difficulties, such as obtaining essential electrical parameters and filling gaps with general knowledge of industry equipment, and the ability to quantify the effect of such substitutions and assumptions on model accuracy.

8.3 OEM PROVIDED MODELS & CALCULATIONS

8.3.1 Many major marine power system OEMs offer modelling services. Their access to equipment parameters and test data can reduce uncertainty and the verification burden. The competence of the provider, the adequacy of the supporting information and any need for independent review should be considered when selecting the provider and reviewing the conclusions.

8.4 THIRD PARTY MODELS & CALCULATIONS

8.4.1 A large number of third party power system consultants offer modelling services, including those associated with the major Classification Societies. Not all of them are familiar with the particular features of marine power systems, and this should be considered in the selection process.

8.4.2 There may be good reasons to choose a third party that is new to marine modelling. In that case the particular features of marine systems should be discussed at the outset, and those commissioning the work should expect that some additional familiarisation may be needed to close any gaps.

8.4.3 Third party providers may need access to proprietary models or to information on bespoke protective functions. The information required, the confidentiality arrangements and the way any access limitations will be handled should be agreed before the work is relied upon.

9 TEST PLANNING

9.1 WRITTEN TEST PLAN

9.1.1 Sections 9 and 10, and the reporting guidance in Sections 11.1 to 11.8, apply where testing forms part of the evidence for the basis of confidence. They do not imply that testing is required in every case.

9.1.2 A written test plan should be prepared before testing begins. It should explain what is to be demonstrated, why that evidence is needed and how it supports the vessel's redundancy concept. The structure described in IMCA M190 (or IMCA M191 for mobile offshore drilling units) may be a useful starting point, with the scope developed for the fault ride-through conclusions and the requirements applicable to the vessel.

9.1.3 For repeatability, the test plan should include the following:

1. Detailed vessel configuration.

   A description of the vessel's DP system architecture, including power generation, distribution and control systems, covering all intended operating configurations.

2. Test and measurement equipment requirements.

   A list of the equipment needed to carry out, monitor and record each test, including sensors, data loggers and any fault simulation or injection tools. The equipment should be suitable for the intended measurements (magnitude, accuracy and sample rate) and calibrated to recognised standards.

3. Installation procedures and test point identification.

   Instructions for installing the test equipment, with diagrams identifying the test points. This supports consistency across repeat trials and independent verification.

4. Data collection requirements.

   The data needed to assess the result, including the recording resolution, format and retention period. Records should be time correlated accurately enough to establish the sequence of events and the response.

5. Expected results and acceptance criteria.

   The functions to be retained and the limits used to judge their performance. Acceptance criteria should be aligned with the vessel's redundancy concept and WCFDI, and should be measurable where this is needed to distinguish acceptable from unacceptable responses.

6. Results recording template.

   A structured format for recording outcomes, timestamps, observations, deviations and witness signatures, to support traceability.

9.1.4 LV systems can have a large number of possible configurations. It is advisable to select configurations that represent the vessel's operating modes and loading conditions, including variations in thruster loading, generator arrangements and the status of industrial or mission equipment.

9.1.5 The reasons for selecting representative cases should be recorded. Similarity of equipment or nominal voltage is not sufficient on its own. The selected cases should cover the differences that could change fault propagation, protection operation or the ability of the remaining equipment to continue its function.

9.1.6 The most demanding condition may be different for each conclusion. A strong source may impose the greatest fault duty, while a weak or current limited source may not provide enough current for prompt clearance. Load, stored energy, operating mode and equipment condition should therefore be considered together. Not every combination needs to be tested where analysis and other evidence show that the selected cases cover the intended operating arrangements.

9.2 PRE-CONDITIONS FOR TESTING

9.2.1 Commissioning of the systems relevant to the proposed tests should be complete enough to give a safe and representative initial condition. Outstanding work should be reviewed for its effect on the test, the expected response and the validity of the evidence. Items that affect safety or would invalidate the test should be resolved first.

9.2.2 Relevant commissioning evidence may include the following, depending on the installed equipment and the conclusions to be demonstrated:

- Verification of earth fault protection logic.
- Secondary injection testing.
- Verification of the installed current and voltage sensing and trip paths, including primary injection where appropriate.
- Generator commissioning, including load step testing.
- DP control system and thruster commissioning.
- Functional testing of arc detection, where fitted.

9.3 PROTECTIVE FUNCTIONS TO BE REVIEWED

9.3.1 The protection arrangements should be reviewed before test planning is completed. The review should establish whether the installed functions, settings, sensing, trip paths and supporting supplies can contain the identified faults in each intended operating configuration. Testing cannot compensate for an unresolved design deficiency.

9.3.2 The protective functions relevant to the redundancy concept should be identified in the FMEA and the protection studies. Depending on the arrangement, they may include:

- **Earth fault protection.** The means of detecting earth faults and, where required, selectively isolating them should suit the earthing arrangement and the intended failure response.
- **Overcurrent protection.** Time graded, directional, differential and voltage dependent overcurrent schemes should be considered.
- **Undervoltage trip delays.** Undervoltage functions should be coordinated so that equipment intended to survive is not disconnected during a disturbance it is intended to tolerate. This should be reconciled with equipment protection and the required fault isolation.
- **Drive DC bus under and overvoltage protection.** Protection of drive DC links, converters and energy storage should be coordinated with their operating limits and the required ride-through response. An action that protects one item may remove power or control from others, and these consequences, including blocking, shutdown and recovery, should be included in the assessment.
- **Arc protection.** Where fitted, the zone of coverage, the dependencies and the coordination of arc protection with the conventional protection should be established (see Section 6.15).

- **UPS output and final distribution protection.** The operation of UPS output protection and of the fuses and circuit breakers in final distribution should be established in each defined supply state (see Sections 6.11 and 6.12).

9.4 DISTURBANCE ENVELOPE AND TEST COVERAGE

9.4.1 The test plan should define the disturbance that the equipment is expected to withstand and the basis for that expectation. Relevant characteristics may include the depth and duration of a voltage dip or interruption, the recovery, any overshoot, frequency change or DC voltage variation. The profile should follow from the fault studies, the installed equipment and the applicable requirements. The method selected should reproduce, or otherwise provide valid evidence for, the characteristics relevant to the conclusion. Section 16.5 gives a worked example.

9.4.2 VOLTAGE EXCURSION RIDE-THROUGH

9.4.2.1 Undervoltage ride-through should be assessed against the voltage expected at the equipment terminals during the relevant faults. The duration should cover the complete fault clearance process and any protection failure case on which the redundancy concept depends. Where uncertainty affects the conclusion, a justified allowance should be included.

9.4.2.2 Voltage recovery should be part of the assessment. Overshoot, delayed recovery and repeated dips may matter as much as the initial minimum voltage. The required behaviour should be established from the characteristics of the generators, converters, energy storage and loads. A single percentage of nominal voltage is not a suitable acceptance basis for every LV AC or DC system.

9.4.2.3 Equipment immunity information prepared to IEC 61000-4-11 or IEC 61000-4-34 (AC input ports) or IEC 61000-4-29 (DC input ports) can help establish how an item responds to a disturbance at its terminals. It relates to the item as tested and to standard test levels, and it does not cover the supporting services or the installed arrangement. It should be compared with the envelope derived for the point of use before it is relied upon.

Note: *The type of excitation support may be influential in the verification and validation process. For example, Permanent Magnet Generators (PMGs) are less vulnerable to becoming hidden failures than excitation systems based on using CTs to derive excitation power from the fault current. In some cases it may be necessary to model or test fault ride through with and without the current boost function active.*

9.4.3 CURRENT-SENSING AND PROTECTION VERIFICATION

9.4.3.1 Current injection tests should demonstrate the sensing, protection and trip functions included in the test circuit. The stimulus should suit the equipment and the protection characteristic being examined. The record should identify which parts of the installed protection chain were exercised and which were assessed by other means.

9.4.3.2 Polarity, phase association, measurement scaling and direction should be verified where they affect fault detection or selectivity. The evidence should cover the intended flow directions and protection zones. Low voltage current injection does not demonstrate interruption at the vessel’s service voltage or the response of the connected consumers.

9.4.4 EARTH-FAULT RESPONSE

9.4.4.1 Earth fault verification should reflect the earthing arrangement and the intended response to the relevant faults. The objective may be detection, selective isolation or confirmation that a first fault does not cause an unacceptable loss of equipment. The expected response should be established before the method is selected.

9.4.4.2 Representative locations may be used across the agreed configurations where their coverage is justified. The method should take account of the actual return paths and the

limitations of the test stimulus. Opening a bus tie, or using a particular fault current, is not appropriate for every system.

9.4.5 EQUIPMENT AND DP FUNCTION

9.4.5.1 Thruster loading and direction should be selected to examine the relevant loss of thrust and recovery mechanisms, and to establish whether the surviving thrusters keep the performance the redundancy concept needs during and after the disturbance.

9.4.5.2 Kinetic buffering and stored energy may contribute to ride-through. Where that contribution supports redundancy, its effect on speed, torque, available thrust and recovery should be understood. A drive that remains energised has not necessarily maintained the required thrust.

9.4.5.3 Measurements should be chosen to demonstrate the behaviour being claimed. Drive data may be useful alongside electrical measurements and evidence of the actual thruster response. Internal drive signals should be accessed only where this is appropriate for the equipment and can be done safely.

9.4.5.4 The evidence should cover the complete DP function, including the supporting supplies and services identified in the FMEA. Where integrated vessel testing is used, the configuration should allow the claimed response to be observed. Conclusions should address the local subsystem, running generators, thrusters, position and heading. Any temporary reduction in

capability should be assessed against the agreed acceptance basis. Station keeping may be affected even where no equipment trips.

9.5 ACCEPTANCE CRITERIA

9.5.1 Acceptance criteria should be agreed before testing. They should state the behaviour needed to support the redundancy concept and the evidence needed to demonstrate it, and should be measurable where this is needed to distinguish an acceptable response from an unacceptable one.

9.5.2 The applied disturbance and test configuration should be shown to be relevant to the conclusion. The fault should be contained as intended, with the expected detection and protective actions, and the resulting loss of power, control and thrust should not exceed the WCFDI.

9.5.3 Equipment intended to survive should retain the required function during the disturbance and the recovery. Where continued operation is required, an automatic restart or operator intervention should not be accepted as equivalent unless there is an explicit basis for it in the agreed design and acceptance criteria.

9.5.4 The effect on position, heading and mission equipment should be assessed against the vessel specific criteria. The criteria should also cover restoration of the surviving system to a stable condition and identify any limitations on further operation.

9.6 MEASUREMENT POINTS

9.6.1 The test plan should specify the measurement points needed to verify fault ride-through capability and, where applicable, the recording scale and resolution. If recordings are event triggered, the trigger should be identified in the test plan and set up before testing.

9.6.2 Measurement points should be chosen to show the disturbance, the protection response and the effect on the equipment whose continued operation is claimed. Suitable sources include voltage and current measurements, protection records, generator and converter data, thruster records and DP event logs. AC and DC measurements need sensors and recorders suited to the signals involved.

9.6.3 Pre-trigger recording and time correlation should be provided where needed to reconstruct the event, with enough resolution to distinguish the relevant sequence and timing. A timestamped alarm list alone may not resolve a short electrical transient. The recording period should be long enough to capture the subsequent response and stable recovery of the relevant sources, controls and thrusters.

9.6.4 Where practical, signals should be accessible through dedicated test interfaces with standard connectors. This supports safe and repeatable testing and reduces the risk of introducing faults during setup (build to test).

9.6.5 Test equipment should be suitable for the electrical duty, the environment and the accuracy required. Its output waveform and measurement response should suit the test. Connections should be arranged so that the evidence can be obtained without introducing an unassessed common supply, earth path or other dependency.

Note: *The effects of CT saturation should be considered, together with the means employed to mitigate them.*

9.7 CALIBRATION REQUIREMENTS

9.7.1 The basis for confidence in the measurements should be recorded. Instruments should have calibration or other documented verification appropriate to their use, with traceability and uncertainty adequate for the acceptance decision.

9.7.2 Calibration intervals and checks should follow the applicable requirements, the instrument manufacturer's guidance and the organisation's calibration procedures. A calibration certificate does not make up for an unsuitable sensor, incorrect scaling or an inadequate sampling rate.

9.8 RISK ASSESSMENT & MITIGATIONS

9.8.1 The test method should be selected with regard to both the evidence required and the consequences of an unsuccessful test. Low voltage does not imply low fault energy or low equipment duty. The relevant OEMs and competent specialists should be involved where their knowledge is needed to establish equipment limits, test validity or recovery arrangements.

9.8.2 Testing should be subject to the vessel's formal risk assessment process. The required controls and pre-test checks should be identified and confirmed in place before the test begins.

9.8.3 The possibility of an unsuccessful test should be considered during planning. The test plan may include a structured approach for investigating and resolving unexpected results, particularly where they could undermine confidence in the fault ride-through capability of the system.

10 TEST EXECUTION

10.1 EXPERTISE REQUIREMENTS

10.1.1 The testing organisation should have competence appropriate to the installed AC and DC equipment, protection, controls and test methods. The work should be led by persons who understand how the local electrical response can affect the vessel's redundancy concept and station keeping capability.

10.1.2 Responsibilities for test preparation, vessel readiness, conduct of the test, recording, interpretation and return to service should be clear. The vessel specific test programme should be reviewed through the owner's authorised process, with OEM and Class involvement where required. Competence in operating test equipment is not the same as competence to assess the integrated DP response.

10.2 PROTECTION AUDIT & CALIBRATION CHECK

10.2.1 Before testing starts, the following conditions should be met:

- Relevant commissioning is complete, and outstanding work has been reviewed. Defects or unverified items that affect test safety, the initial condition or the validity of the result have been resolved.
- A formal risk assessment has been carried out, and the relevant parties have identified the potential risks associated with the measurement process.
- Protection settings have been checked against the controlled parameter records and the applicable protection studies, and their review and acceptance status is evident.
- Undervoltage and other protective functions have been coordinated with the disturbances to be tolerated, the equipment limits and the intended isolation of faults, using the actual sensing, delay, communication and interruption times of the installed scheme. Generic feeder and generator delay values should not be used for this assessment.

10.2.2 **Protection audit.** The protection audit should confirm that the protection system is set up as designed and ready to be tested. The following should be carried out:

- Confirm that the recording arrangements allow the relevant events to be correlated with sufficient accuracy.
- Verify relay settings against the approved documentation.
- Configure protection device recorders before the test.
- Where synchronised recording is used, confirm that it is working across the relevant protection, thruster and power management systems.
- Manually trigger the logging devices within the test scope and confirm that data is captured correctly.

10.2.3 **Calibration check.** To confirm the integrity of the recorded data, the following checks should be carried out:

- All equipment is used in accordance with the manufacturer's guidance and site specific regulations.
- Recording and measuring devices have calibration or other documented verification appropriate to their use, as described in Section 9.7.
- Where applicable, self-diagnostic routines are run and logged.
- Batteries, probes and measuring cables are visually inspected and are free from visible damage or degradation.

10.3 CONDUCT OF THE FAULT RIDE-THROUGH TESTING

10.3.1 The test plan should be the primary reference for the work. It should define the responsibilities, initial conditions, method and supporting information needed for safe and repeatable testing, and the means of recording what was done and the results obtained.

10.3.2 Where protection settings are changed for testing, the changes should be documented in the test plan and reviewed through the agreed authorisation process, with OEM and other technical input where needed. Their effect on safety, test validity and restoration should be clear.

10.3.3 Relevant records should be secured before equipment is reset or records are overwritten, where this can be done without delaying any action needed for safety. The recording arrangements should allow data to be preserved promptly after an unexpected result.

10.3.4 After each test, protection settings should be returned to their correct values and this should be verified and documented.

10.3.5 Restoration should cover the whole affected arrangement, including temporary wiring, test supplies, software or configuration changes, inhibited functions and equipment operating modes. The condition of the tested equipment and the availability of the required stored energy should be checked. Return to service should follow the vessel's authorised process and take account of any unresolved findings or operating limitations.

10.3.6 Sacrificial (additional) low voltage circuit breakers have been used by some vessel owners to test fault ride through on new build 690V systems purpose built to undergo such testing.

10.4 INTERPRETATION OF TEST RESULTS

10.4.1 Measured values should be logged and compared with the expected outcomes in the test plan to determine whether the acceptance criteria have been met.

10.4.2 All data collected should be reviewed for legibility and completeness. The data set should be sufficient to support a formal test report and any later verification activities.

10.4.3 A result should be judged against the conclusion the test can support. A test that applied an adequate stimulus and produced an unacceptable response is a different outcome from a test that did not reproduce the intended condition or did not capture enough data. Both need to be resolved, but they should be reported separately.

10.4.4 The report should identify what was demonstrated, any conclusion that was only partly demonstrated and anything that remains unverified. Where a limitation affects the configurations in which the vessel may operate, this should be made clear to the owner and the operating team.

10.5 RESPONSE TO UNEXPECTED TEST OUTCOMES

10.5.1 INVESTIGATION OF UNEXPECTED RESULTS

10.5.1.1 An unexpected result should be investigated before the intrusive event is repeated. The investigation should distinguish between a test or measurement error, an incorrect prediction and an actual weakness in the installed system. Repeated application of the fault should not be used as the main means of diagnosis.

10.5.1.2 Controlled diagnostic work may be needed to establish the cause. Before retesting, the suitability of the revised test, the corrective action and the condition of the affected equipment should be reviewed. The scope of retesting should cover the affected conclusions and any earlier conclusions that are no longer valid.

10.5.2 PARAMETER ERRORS

10.5.2.1 Incorrect settings should be investigated and corrected through the controlled change process. The parameter records, protection studies and other affected documents should be reconciled with the final installed state.

10.5.2.2 A setting change may affect more than the test in which the error was found. The effect on previous evidence should be reviewed and the necessary verification repeated. The extent of revalidation should follow from the affected functions and dependencies.

10.5.2.3 Note: *Model Based Testing has been a useful method of establishing the efficacy (and correct parametrisation) of protection settings. It is not a substitute for a dedicated protection settings review but provides an additional barrier.*

10.5.3 OTHER ERRORS

10.5.3.1 Wiring, sensing or connection defects should be corrected and the affected functions verified again. The review should consider whether the defect is isolated or may also exist in similar equipment or other redundancy groups. Drawings and installation records should be updated to reflect the verified arrangement.

10.5.3.2 An intermittent result should not be dismissed because a later test was successful. Intermittent faults should be managed in accordance with TECHOP D-12. The cause, its possible effect on the redundancy concept and the evidence supporting its resolution should be recorded.

10.5.3.3 Means to establish the '*margin for error*' or how close a test was to failure are additional confidence builders.

11 REPORTING AND HANDOVER

11.1 INTRODUCTION

11.1.1 This section gives guidance on the structure and content of reports on fault ride-through testing and on the handover of the basis of confidence. A report should give an independently verifiable account of the work, with emphasis on substantiating the vessel's redundancy concept and demonstrating single fault tolerance, so that Classification Societies, owners, operators and other stakeholders can evaluate the conclusions.

11.2 ASSURABLE FORMAT

11.2.1 The report format should support independent verification of the conclusions, with clear identification of test objectives, methods, results and supporting evidence. Structured templates are recommended to give consistency across trials programmes and to help review by Classification Societies and other stakeholders.

11.2.2 Each section should be clearly labelled and contain enough detail for an independent party to reach the same conclusions as the author. Annotated screenshots, trends and system diagrams should be used where they improve clarity. References to Classification Society rules and OEM specifications should be given where applicable.

11.2.3 The report should summarise any deviations from the planned procedures and their effect on the validity of the results. Where tests were repeated or modified, the reason should be recorded. Observations should be traceable to the data sources used.

11.3 DATA CENTRICITY

11.3.1 Data centricity means giving priority to independently verifiable data in the verification and validation process. For fault ride-through, this means that outcomes should be supported by data demonstrating the performance, protection and detection elements of the system. Digital data from protection relays, power management systems and event recorders is preferred.

11.3.2 Where digital infrastructure is limited, image based data (for example screenshots and video) may be used, provided it is presented in an assurable format. The report should identify the data sources supporting each outcome and describe how the data was collected. Using several independent data sources improves confidence in the results.

11.3.3 The format and fidelity of the data should also be considered. Digital data should be time synchronised and traceable to the test event. Image data should be legible and annotated where necessary. Observers should avoid terms such as "as expected" unless they are supported by corroborating evidence. Where simulation is used, the data should be presented in a way that allows comparison with the live test results.

11.4 REQUIREMENTS FOR REPORT

11.4.1 An LV fault ride-through test report should include the following:

- **Introduction.** A concise overview of the programme, describing the scope, the systems and configurations evaluated, and the reasons for the tests, with reference to the vessel's redundancy concept and the performance, protection and detection elements being verified.
- **Applicable rules and standards.** The Classification Society rules, Class notations and industry standards applicable to the vessel and the scope of testing.
- **Test objectives and acceptance criteria.** The intent of each test and the expected system behaviour under fault conditions, with criteria agreed before testing by the parties responsible under the vessel's verification arrangements.

- **Link to the redundancy concept.** How each test supports the redundancy concept and single fault tolerance, and which of the four conclusions in Section 4.1 it addresses.
- **Risk assessment.** Confirmation that the owner's approved risk assessment process was followed, that any additional risks identified during planning were addressed, and that the safety controls were in place during testing.
- **Test methodology.** How each test was carried out, using structured test sheets with fields for expected results, actual results and supporting evidence.
- **Simulation methodology.** The modelling tools and any real time simulation (RTS) or hardware in the loop (HIL) arrangements used, the important assumptions, the basis for identifying the most demanding conditions, and the limits on extending the results to configurations that were not tested.
- **Results.** The data collected, presented in a structured and assurable format, including waveform captures, alarm and event log extracts and simulation outputs. Anomalies, unexpected behaviour and deviations from expected results should be identified and explained.
- **Conclusions.** The key findings, a statement of whether the power system demonstrated fault ride-through capability against the acceptance criteria, and any areas requiring further investigation, testing or corrective action.

11.5 CALIBRATION CERTIFICATES

11.5.1 The report should identify the instruments used and include or reference the relevant calibration and verification records. Any limitation in range, accuracy, time correlation or recording response that affects the interpretation should be stated.

11.6 WAVEFORMS

11.6.1 Waveform captures should be provided where they are needed to show the disturbance, its clearance or the equipment response. They should have suitable scaling, time resolution and annotation so that an independent reviewer can understand the event and assess the conclusion.

11.6.2 The report should identify the source of each waveform and confirm that the sampling rate was high enough to capture the transient. Any anomalies should be highlighted and explained, and comparisons with expected waveforms or model predictions included where applicable.

Note: *COMTRADE (Common Format for Transient Data Exchange), defined in IEEE C37.111 and IEC 60255-24, is widely used for the collection and exchange of power system transient and test data. There are several variants within the standard. The parties involved in the testing process should agree which is to be used and confirm that their equipment can read and write it.*

11.7 ALARM & EVENT LOG EXTRACTS

11.7.1 Alarm and event log extracts provide evidence of fault detection. They should include timestamps, alarm descriptions and the system actions taken, and be presented in a structured format linked to the relevant test objectives.

11.7.2 Logs may be taken from the DP control system, IAS, VMS, PMS, integrated data loggers and protection devices, each of which may provide different detail and resolution. Where the VMS or PMS forms part of the IAS, the report should identify the originating function or subsystem rather than treating all IAS records as independent data sources. Where records overlap, they should be compared to build a consistent account of the event. The report should identify the relevant alarm settings and any difference between the configured and intended response.

11.7.3 Alarm and event data should be presented so that it can be correlated with other evidence such as waveform captures. Where alarms did not occur as expected, the reasons should be investigated and recorded.

11.8 COMPARISON TO MODELS

11.8.1 Where simulation or model based testing is used, the report should compare the observed behaviour with the predicted outcomes. This information should be used to validate and improve the model.

11.8.2 Results should be presented as overlays, trends or tables. Deviations from the predicted behaviour should be identified, and the report should state whether they affect the validity of the model or the conclusions of earlier simulations.

11.8.3 A validated model may be used to examine fault scenarios or configurations that were not tested live, within the limits described in Section 8.1. This can reduce the verification and validation burden and extend the basis of confidence.

11.9 HANDOVER OF THE BASIS OF CONFIDENCE

11.9.1 The final records should allow the owner to identify the arrangement for which fault ride-through has been demonstrated and the conditions on which that conclusion depends. This includes the relevant equipment, operating configurations, software and settings, the limits of the evidence and any unresolved matters.

11.9.2 A concise summary should link the conclusions in the FMEA to the supporting calculations, OEM information and test records. Section 16.6 shows one way of presenting this. Evidence may be referenced in existing controlled documents and does not need to be copied into a separate report.

11.9.3 The conclusions and supporting evidence should be reflected in the vessel's DP FMEA, which is the controlled document recording the failure effects and compensating provisions. IMCA M166 and TECHOP D-05 apply to the content and review of that document.

11.9.4 The handover should identify the attributes that need continuing attention, who is responsible for them and how they will be maintained. These may include protection integrity, stored energy availability, equipment condition, operating restrictions and the validity of models and parameter records. The operating team should be able to recognise when an assumed condition no longer applies.

12 COMPARISON OF AVAILABLE METHODS

12.1 MODELLING

12.1.1 Modelling can help identify the most demanding faults and operating conditions, explain the expected response and extend the coverage of physical tests. Its value depends on the quality of the input data and on evidence that it represents the behaviour relevant to the conclusion. The level of detail should be proportionate to the system and the conclusion; a complex dynamic model is not needed for every simple circuit.

12.1.2 Physical testing demonstrates selected functions of the installed system and may also be used to validate the model. Where the model is then used for untested configurations, the basis for doing so should be explained. Agreement for one event does not validate every modelled behaviour or operating condition.

12.1.3 Real time simulation (RTS) and hardware in the loop (HIL) testing can expose actual protection or control devices to representative signals without imposing the duty of a live fault. They provide useful evidence of logic, timing and interactions. Their limitations should be stated, particularly where sensors, wiring, trip devices, physical interruption or equipment power behaviour are outside the test boundary.

12.2 SECONDARY INJECTION

12.2.1 Secondary injection applies representative signals to a protection device. It demonstrates the response of the functions, settings and logic included in the test. Where the installed trip circuit and circuit breaker are included, their response can also be verified. The report should state the actual test boundary; injection at a relay does not prove the whole protection system.

12.2.2 Secondary injection is normally most useful early in the verification programme, so that logic and setting errors can be resolved before more demanding tests. The sequence should suit the installed equipment and the methods selected.

12.2.3 Coverage should follow the protection functions required by the redundancy concept, including alternative trip paths and failure cases. Tests of individual relays should not be described as proof of network coordination unless the necessary interactions have also been demonstrated.

12.2.4 The continuing verification programme should take account of the applicable requirements, OEM recommendations, the detectability of failures and experience in service. This TECHOP does not prescribe a standard interval for secondary injection. Records should make clear which functions were exercised and which were outside the scope.

12.3 OPERATION OF CIRCUIT BREAKERS

12.3.1 SUPPLY INTERRUPTION AND RESTORATION

12.3.1.1 Controlled interruption and restoration of a supply may be used to examine the response of equipment to a loss of voltage. This is sometimes called breaker operation or “bang-bang” testing. The useful evidence is the disturbance measured at the equipment and the response of that equipment.

12.3.1.2 The method does not reproduce the fault current of a short circuit and may not reproduce the residual voltage, phase changes, source response or recovery that follow fault clearance. Its suitability should therefore be judged against the particular ride-through conclusion.

12.3.1.3 The test boundary is: source, controlled supply disturbance, equipment and supporting services, observed function. The test establishes behaviour within that boundary. Protection selectivity and fault interruption at service voltage need their own supporting evidence.

12.3.1.4 TECHOP D-07 Section 8.5.1 records that inrush current on reclosing can trip circuit breakers in a way that is not representative of recovery from a real short circuit. The suitability of this method should be confirmed for each application, taking account of transformer energisation and motor re-acceleration on restoration of the supply.

12.3.2 ALTERNATIVE SUPPLY ARRANGEMENTS

12.3.2.1 An alternative supply arrangement may give better control of the interruption and restoration. Its suitability depends on the sources, interlocks, equipment duty and the disturbance to be represented. Having two breakers in the arrangement does not make the test representative or safe.

12.3.2.2 The chosen arrangement should be explained in the vessel specific test plan, which should show how unintended energisation, back feed or connection of unsynchronised sources is prevented and how the normal configuration is restored.

12.3.3 AUTOMATED OPERATION OF CIRCUIT BREAKERS

12.3.3.1 Automated switching devices may be used to control the test duration more precisely. These devices often include high speed data capture and give consistent timing.

12.3.4 TESTING FOR WORST CASE FAILURE

12.3.4.1 The interruption duration should be justified by the relevant fault clearance envelope, including any backup action relied upon in the redundancy concept. The comparison should use the complete time taken to remove the disturbance, not a relay setting in isolation.

12.3.4.2 A controlled interruption may bound a particular undervoltage exposure, but it is not the worst case for every mechanism. Its relevance should be checked against the AC or DC arrangement and the response of the connected equipment.

12.3.4.3 The limitations of the switching arrangement should be understood before it is used. Operating times, recharge requirements and interlocks may limit the duration or repeatability of the disturbance, and temporary changes can alter the behaviour the test is intended to prove.

12.3.4.4 The applied voltage and timing should be measured; a command to open or close is not evidence of the voltage seen by a consumer. A disturbance shorter than intended can give false confidence, while a longer or different disturbance can place unnecessary duty on the equipment or invalidate the comparison.

12.3.4.5 The method selected should provide useful evidence at an acceptable risk. Manual or automated breaker operation tests should be combined with the other evidence needed to demonstrate the complete fault ride-through conclusion.

12.4 VOLTAGE TRANSIENT WAVEFORM GENERATION

12.4.1 A fault may cause an initial voltage disturbance, a period before isolation and a recovery transient before the supply settles. In an AC generator fed system, recovery may include an overshoot caused by the AVR response. Converter fed and DC systems can respond differently.

12.4.2 Figure 12-1 illustrates these stages for an AC example. It is an explanatory diagram, not a prescribed test waveform. The relevant profile should be established from the installed arrangement and the fault being assessed.

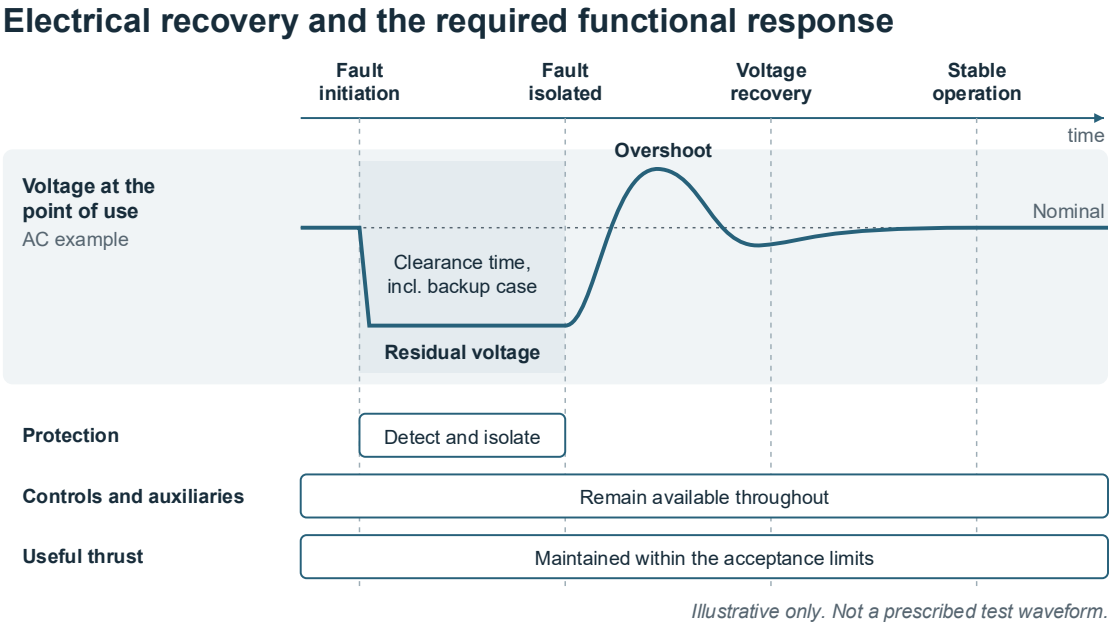


Figure 12-1 Electrical recovery and the required functional response

12.4.3 Voltage disturbance generation can provide evidence of the response of connected equipment to a defined input. The method should cover the relevant recovery characteristics as well as the initial dip. The response of the vessel's own sources to a fault needs separate evidence.

12.4.4 Where the behaviour of the installed AVR or converter controls is part of the conclusion, it should be supported by suitable evidence. The relevant disturbance duration comes from the actual fault clearance process, including the applicable protection failure case. It should not be based by default on the long-time overcurrent setting of a bus tie.

12.5 PRIMARY INJECTION

12.5.1 Primary injection passes a test current through the primary conductor or sensing arrangement. It can provide evidence of the installed current measurement chain, including polarity, scaling and connections. Where the relay, trip circuit and breaker are included, their response can also form part of the evidence.

12.5.2 The test boundary and stimulus should suit the sensing technology and the functions being assessed. CTs, Rogowski coils, electronic sensors and their interfaces do not all respond to the same test signal in the same way.

12.5.3 Primary injection can reduce uncertainty about the installed sensing and protection chain. It does not establish switchgear withstand, interruption at service voltage or the ride-through of connected equipment. Installing and connecting the test equipment also carries risks that should be assessed.

12.5.4 Existing primary injection evidence may remain useful where it can be traced to the installed equipment and the arrangement has not changed. Whether further testing is needed should be decided from the applicable requirements, OEM guidance, maintenance history and any changes to the sensing or trip path.

12.5.5 Continuing verification should recognise both fixed installation attributes and components whose condition or performance may change. A commissioning record should not become a blanket exemption from further verification. Equally, a repeat high current test should not be specified where suitable evidence already demonstrates that the attribute is unchanged.

12.5.6 Current sensing failures can cause failure to clear a fault, incorrect isolation or loss of healthy equipment. The verification scope should follow these failure effects and the protection functions on which the redundancy concept depends.

12.6 MODULATION OF THE AUTOMATIC VOLTAGE REGULATOR

12.6.1 A voltage disturbance can be produced by modulating the excitation of one or more generators through their AVRs. Modern digital AVRs usually provide the necessary control. The depth, duration and recovery of the disturbance can be specified and repeated without applying a fault or interrupting a supply.

12.6.2 The method can provide evidence of the response of connected equipment and its supporting services to a defined voltage disturbance. It is well suited to verifying the contactor and relay attributes in Section 6.17 and equipment immunity in general. It applies the disturbance to the whole connected section, which is useful where the combined response of the surviving group is of interest.

12.6.3 The method produces no fault current and therefore provides no evidence of fault detection, selective isolation or equipment duty. The achievable rate of change of voltage is limited by the excitation system and the machine and may not represent the initial collapse caused by a close up fault, so the profile achieved should be measured at the point of use. The effect of the modulation on the machine, its excitation system and its protection, and the interaction with other AVRs operating in parallel, should be agreed with the OEM before the test.

12.7 BUS EXCITATION BY VARIABLE SPEED DRIVE

12.7.1 A section of the distribution can be energised from a variable speed drive (VSD) or other converter whose output can be modulated, to apply a specified voltage disturbance to the equipment on that section. The method gives close control of the depth, duration, rate of change and recovery of the disturbance and can be repeated at low duty.

12.7.2 It is applicable where a section can be isolated and supplied in this way, which in practice is most often a service or distribution level. It can show the response of the connected equipment and the combined response of a group of loads, and allows the disturbance to be applied at a point of use for which an envelope has been derived.

12.7.3 The arrangement is a temporary configuration and should be assessed as one. The test plan should cover isolation, interlocking, prevention of connection of unsynchronised sources or unintended energisation, and restoration of the normal arrangement. The converter's fault current capability and harmonic content differ from those of the installed generation, so the evidence relates to the equipment response to the applied disturbance and not to the behaviour of the vessel's own sources.

12.8 CONNECTION OF HIGH INRUSH LOADS

12.8.1 A voltage dip can be produced by connecting one or more loads with a high inrush current, individually or in quick succession. The method uses installed equipment and needs little temporary arrangement.

12.8.2 The depth and duration of the dip depend on the load, the source and the system impedance and cannot be directly controlled. The profile should therefore be measured, and the method is better suited to confirming a margin than to demonstrating performance against a defined envelope. Repeatability is limited for the same reason.

12.8.3 The duty on the switched equipment, and on any transformer energised as part of the method, should be assessed. The limitation in TECHOP D-07 Section 8.5.1 also applies: inrush current may operate protective devices in a way that is not representative of recovery from a fault.

12.9 APPLICATION OF A FAULT THROUGH A LIMITING IMPEDANCE

12.9.1 A fault may be applied through an inserted impedance to limit the current to a value within the assessed capability of the equipment and its previous service. The method produces real fault current and can provide evidence of fault detection, operation of the sensing and trip path, and the response of connected equipment to a disturbance produced by an actual fault.

12.9.2 The relationship between the limited current and the prospective fault current should be established and the supported conclusions identified accordingly. A test at reduced current may demonstrate detection and discrimination at that current, but not equipment duty at the prospective value. Where the protection characteristic depends on current, the timing observed will not be that of an unlimited fault.

12.9.3 The impedance, its rating and connection, and its behaviour during the test are part of the test arrangement and should be assessed as such, including the consequence of its failure. The method should be considered only where the risk assessment described in Section 9.8 supports it and the effect on the equipment and its permitted further service has been agreed with the OEM.

12.9.4 Applying a fault at a service transformer secondary, where calculation shows that the fault current at that level is within the rating of the equipment, is a variant of this approach and is described in TECHOP D-07 Section 10.2. It can confirm the ride-through capability of the auxiliary equipment supplied at that level. It does not demonstrate the behaviour of the main generation and distribution system.

Note: *Care should be taken not to destroy the fly-wheel diodes on a drive when performing short circuit tests at inverter / converter inputs.*

12.10 SUMMARY COMPARISON OF METHODS

12.10.1 Table 12-1 summarises the contribution of each method to the four conclusions in Section 4.1, the duty it imposes and its main limitation. The conclusions are numbered as in Section 4.1:

1. The equipment can tolerate the disturbance at its terminals.
2. The protection can detect and isolate the fault selectively.
3. The equipment is suitable for the electrical and mechanical duty.
4. The installed DP system retains the desired station keeping capability.

12.10.2 “Partial” means that the method supports the conclusion only within a stated boundary, which should be recorded with the result.

Table 12-1 Contribution of methods to the fault ride-through conclusions

Method	1	2	3	4	Duty	Main limitation
Modelling and calculation	Partial	Partial	Partial	Partial	None	Predictive only. Limited by input data quality and the range over which the model has been validated against measurement.
RTS / HIL	Partial	Partial	No	Partial	None	Tests actual logic and timing. Sensors, wiring, trip devices, interruption and equipment power behaviour are outside the test boundary.
Controlled live short-circuit test of an SSCB	Yes	Yes	Partial	Partial	Low to high	Strong end-to-end evidence for the tested fault locations, configurations and operating conditions. Cumulative equipment duty and untested conditions still require ratings, analysis and OEM evidence. Conclusion 4 depends on observing the integrated DP response.

Method	1	2	3	4	Duty	Main limitation
SSCB BITE and continuous supervision	No	Partial	No	No	None or very low	Coverage depends on the diagnostic design and where the test stimulus enters the protection chain. Some hidden failures may remain outside the diagnostic boundary.
Commanded SSCB operation	No	Partial	No	Partial	Low	Demonstrates the command, gate-drive and switching path included in the test. Does not prove automatic fault detection, interruption at prospective fault current or associated energy absorption.
Secondary injection	No	Partial	No	No	Low	Covers the functions, settings and logic within the injection boundary only.
Primary injection	No	Partial	No	No	Low	Covers the installed current sensing chain. Does not show withstand, interruption at service voltage or consumer ride-through.
Circuit breaker operation	Partial	No	No	Partial	Low to medium	No fault current, residual voltage or source response. Inrush may give unrepresentative results.
Voltage transient generation	Yes	No	No	Partial	Low	Defined, repeatable input. Does not show how the vessel's own sources respond to a fault.
AVR modulation	Yes	No	No	Partial	Low	Applies a defined profile to the whole section. Rate of change limited by the excitation system; no fault current.
VSD bus excitation	Yes	No	No	Partial	Low	Close control of the profile at a point of use. Temporary configuration; source differs from installed generation.
High inrush load connection	Partial	No	No	Partial	Low to medium	Profile neither controllable nor repeatable; should be measured.
Fault through limiting impedance	Yes	Yes	Partial	Partial	Medium to high	Real fault current at a controlled value. Duty at prospective fault current not shown.

Method	1	2	3	4	Duty	Main limitation
Fault at service transformer secondary	Yes	Partial	Partial	Partial	Medium	Confirms ride-through of auxiliaries at that level only (TECHOP D-07 Section 10.2).
Integrated vessel testing	Partial	Partial	No	Yes	Medium	The only method that shows the integrated DP response. Configuration must allow the response to be observed.
Equipment type test / OEM qualification	Partial	No	Yes	No	None	Relates to the equipment, not the installation. Does not cover installed wiring, settings, polarity or trip paths.

12.10.3 The table is an aid to selecting a proportionate combination of methods. It does not replace the assessment described in Sections 7.6 and 9.1, and no entry is an automatic substitute for a test required by an applicable requirement.

12.11 COMBINING METHODS

12.11.1 The selected methods should form a coherent body of evidence. Each should have a clear purpose, and the limitations of one should be covered by others.

12.11.2 A programme may combine design and protection studies, OEM qualification, modelling, protection injection, controlled voltage disturbances and integrated vessel testing. The right combination depends on the arrangement, the available evidence and the applicable requirements. No combination described in this TECHOP is an automatic substitute for a required test.

12.11.3 No single method in Table 12-1 addresses all four conclusions. The programme should be put together so that each conclusion relied upon in the redundancy concept is addressed by at least one method, with the limitation of each method covered by another. Any conclusion not addressed should be recorded as a gap in the basis of confidence.

13 NETWORK & CONTROLS TESTING

13.1 CONSIDERATIONS

13.1.1 The electrical disturbance should be considered together with the response of the networks and controls on which power, thrust and station keeping depend. A power circuit may ride through while a controller, communication path or supporting supply fails. The scope should therefore follow the dependencies identified in the FMEA.

13.1.2 The assessment should include loss, interruption or corruption of control and protection communications where these could affect fault containment or the surviving DP function. Shared power supplies, switches, gateways and control interfaces should be examined for paths that could defeat the intended separation between redundancy groups.

13.1.3 The evidence should establish the required behaviour during the disturbance, any transfer to a surviving path and the subsequent recovery. The response to missing or stale information should be understood. Restoration of communication should not cause an unintended command, trip or reconnection.

13.1.4 The extent of testing should follow the conclusion and the failure effect. Existing network and control system assurance may contribute to the basis of confidence where it covers the actual arrangement and the relevant operating state. Repeating an unrelated network test does not show the response to a power system disturbance.

13.1.5 Results should be related to the local subsystem, running generators, thrusters, position and heading. Where the design accepts a temporary loss of data or control, its duration and consequences should be supported by evidence. An operator display that stays active may hide a loss of function in the controlled equipment.

13.2 REFERENCE GUIDANCE

13.2.1 The following guidance should be used alongside this TECHOP where relevant to the installation: TECHOP D-02 for the selection and interpretation of FMEA test evidence; IMCA M206 for the design and failure behaviour of DP electrical power and control systems, including DC distribution and UPS arrangements; IMCA M259 for the management of DP system network storms; and IMCA M247 for the identification of DP system components and their failure modes. The applicable edition and scope should be recorded in the vessel’s assurance records. A reference in this TECHOP does not make every provision of the referenced document applicable.

13.2.2 The verification programme should address the interfaces between suppliers as well as the individual systems. Responsibilities for the expected failure behaviour, supporting information and resolution of inconsistent results should be agreed, and should remain clear when software, network arrangements or equipment are changed.

14 CONCLUSIONS AND SUGGESTED IMPLEMENTATION STRATEGY

14.1 GENERAL CONCLUSIONS

14.1.1 The following conclusions were reached in the development of this TECHOP:

1. There is a case for action. DP vessels operating with a common power system can be exposed to fault propagation paths that are removed when the systems are separated. The ability to detect and contain those faults, and to maintain the required surviving function, should be supported by evidence that reflects the actual AC or DC arrangement and its intended configurations.
2. Nothing in this TECHOP is intended to exclude other methods of demonstrating fault ride-through capability, and nothing in it requires a particular test to be carried out.
3. An open main bus tie does not remove every ride-through requirement. The FMEA should establish whether auxiliary supplies, control power, UPS arrangements, converters, networks or other connections can propagate a disturbance to equipment intended to survive. Where a fault cannot affect the surviving system, the reason and the supporting evidence should be recorded.
4. Vessels that may operate with a common power system in TAM may still need some evidence of ride-through capability, proportionate to the consequences of loss of position in TAM, to meet stakeholder expectations.
5. For newbuilds, the build to test philosophy should provide connection points for test equipment and suitable logging facilities.
6. LV covers arrangements with very different source, protection and recovery characteristics. Confidence should be built from the relevant failure mechanisms and required functions. The nominal voltage or the technology used is not a sufficient basis.

14.1.2 The verification burden can be reduced by selecting suitable methods, reusing valid evidence and designing equipment for testing. It should not be reduced by leaving a material failure effect unresolved.

14.1.3 The basis of confidence should remain identifiable throughout the life of the vessel. Changes, deterioration and experience in service should be assessed against the attributes on which it depends.

14.2 SUGGESTED IMPLEMENTATION STRATEGY

14.2.1 DP industry guidance (IMCA, MTS and USCG) recommends carrying out critical DP activities in the DP system configuration that offers the highest station keeping integrity. What constitutes a critical activity is outside the scope of this TECHOP; guidance is given in TECHOP O-03, “Defining Critical Operations Requiring Selection of Critical Activity Mode”.

14.2.2 This TECHOP gives guidance on demonstrating and maintaining fault ride-through capability in LV AC and DC power and control systems, for new vessels and vessels in service. The applicable Class and Flag requirements, the vessel’s accepted design basis and other stakeholder expectations should be established before an assurance programme is agreed. The following approach is suggested:

1. For new vessels, the intended operating configurations and assurance objectives should be agreed early enough to influence design, equipment selection and test access. The design should identify the attributes needed for fault containment and continued DP function, and how they will be demonstrated and maintained.

2. For vessels in service, the first step is to establish what the existing evidence shows. Missing records, changes since the original tests and differences between the documented and installed arrangement should be identified, and the resulting gaps should guide any further analysis, inspection or testing.
3. Where a different operating mode or Class notation is proposed, the necessary design and verification work should be agreed with the relevant parties. A change to documentation or notation is not a substitute for evidence of the required performance.
4. Repairs and modifications should preserve the relevant characteristics of the equipment and its interfaces. This should be positively verified where the work could affect the basis of confidence, including where an apparently equivalent replacement has different controls, protection or supporting requirements.
5. Owners who foresee a need to operate with a common power system in CAM should be aware that reliance on protective functions adds to the periodic verification and validation burden of the DP system.
6. Owners who do not foresee a need to operate with a common power system in CAM, but who do so in TAM, should consider what evidence of fault ride-through capability is appropriate to that mode and to the consequences of loss of position.

14.3 DEFENDING THE ATTRIBUTES THROUGH THE LIFECYCLE

14.3.1 The owner should keep a controlled record of the arrangement for which the conclusions were demonstrated. The record should link the FMEA, drawings, settings, software and supporting evidence, so that a later change can be assessed against the same design intent.

14.3.2 Continuing verification should concentrate on the attributes that may deteriorate, become unavailable or be altered. These include protection and detection functions, equipment condition, supporting supplies, stored energy and the operational controls needed to keep the demonstrated configuration.

14.3.3 Continuing verification should be delivered through the vessel's existing assurance arrangements where possible. The relevant activities are the annual DP trials programme (IMCA M190, or IMCA M191 for mobile offshore drilling units), the gap analysis process described in TECHOP O-02, continuous trials as described in TECHOP G-03 where applicable, and the periodic review and revalidation of the DP FMEA. Each attribute needing continuing attention (see Section 11.9) should be allocated to one of these, with the responsible party identified. Intervals and methods should follow the applicable requirements, OEM guidance and the vessel's maintenance system.

14.3.4 Changes to hardware, software, settings, connections, operating modes or energy storage arrangements should be reviewed for their effect on the original conclusions. The review should identify the evidence that remains valid and the further verification needed. The scope should be set by the affected function and its dependencies. The apparent size of the change is not a reliable guide.

14.3.5 Faults, unexplained trips, abnormal recovery and near misses should also prompt a review where they call the expected response into question. A successful recovery still leaves the need to understand why a required attribute was lost or failed to operate.

14.3.6 The current state should be clear to the operating team. Unavailable protection, degraded energy storage, unresolved findings and configuration restrictions should be reflected in the relevant operating guidance, such as the ASOG. Responsibility for restoring the required attributes and confirming the evidence should be assigned.

14.3.7 Periodic review should reconcile the evidence, the installed arrangement and experience in service, to confirm that the vessel can still support the same fault containment and surviving function conclusions, or to identify the limits that now apply.

15 REFERENCES

The references below provide related guidance and technical background. The edition applicable to a vessel should be established from its governing requirements and agreed verification basis.

Marine Technology Society DP Committee. TECHOP D-01 Rev1 January 2021, Addressing C³EI² to Eliminate Single Point Failures.

Marine Technology Society DP Committee. TECHOP D-02 Rev1 January 2021, FMEA Testing. https://dynamic-positioning.com/wp-content/uploads/2025/05/TECHOP-D-02-Rev1-Jan21-FMEA-TESTING.pdf

Marine Technology Society DP Committee. TECHOP D-03 Rev1 January 2021, Blackout Recovery.

Marine Technology Society DP Committee. TECHOP D-04 Rev1 January 2021, Evaluation of Protection Systems.

Marine Technology Society DP Committee. TECHOP D-05 Rev1 January 2021, FMEA Gap Analysis.

Marine Technology Society DP Committee. TECHOP D-07 Rev1 January 2021, A Method for Proving Fault Ride-Through Capability of DP Vessels with HV Power. https://dynamic-positioning.com/wp-content/uploads/2025/05/TECHOP-D-07-Rev1-Jan21-PROVING-FAULT-RIDE-THROUGH-CAPABILITY-OF-DP-VESSELS.pdf

Marine Technology Society DP Committee. TECHOP D-11 Rev3 March 2024, Redundancy Concept Philosophy Document. https://dynamic-positioning.com/wp-content/uploads/2025/05/TECHOP-D-11-Rev3-Mar24-RCPD.pdf

Marine Technology Society DP Committee. TECHOP D-12 Rev2 March 2024, Management of Intermittent Faults in DP Systems.

Marine Technology Society DP Committee. TECHOP G-02 Rev1 January 2021, Power Plant Common Cause Failures.

Marine Technology Society DP Committee. TECHOP G-03 Rev1 January 2021, Continuous Trials for DP MODUs.

Marine Technology Society DP Committee. TECHOP O-02 Rev1 January 2021, Annual DP Trials and Gap Analysis.

Marine Technology Society DP Committee. TECHOP O-03 Rev1 January 2021, Defining Critical Operations Requiring Selection of Critical Activity Mode.

Marine Technology Society DP Committee. DP Vessel Design Philosophy Guidelines, Rev2 April 2021.

OCIMF, IMCA DP Committee and MTS DP Committee. JDP01 Rev1, Unified Approach to the Verification, Validation and Assurance of Single Fault Tolerance of DP Systems.

International Maritime Organization. MSC.1/Circ.1580, Guidelines for Vessels and Units with Dynamic Positioning (DP) Systems, 16 June 2017.

International Marine Contractors Association. IMCA M166 Rev3 May 2024, Code of Practice on Failure Modes and Effects Analysis (FMEA).

International Marine Contractors Association. IMCA M190 Rev3.2 May 2024, Code of Practice for Developing and Conducting DP Annual Trials Programmes.

International Marine Contractors Association. IMCA M191 Rev1.1 April 2024, Code of Practice for DP Annual Trials for Mobile Offshore Drilling Units.

International Marine Contractors Association. IMCA M206 Rev2.1 November 2023, A Guide to DP Electrical Power and Control Systems.

International Marine Contractors Association. IMCA M247 Rev0.1 February 2024, Guidance to Identify DP System Components and their Failure Modes.

International Marine Contractors Association. IMCA M250 Rev0.2 April 2024, Introduction to Hybrid Battery Systems for DP Vessels.

DNV. DNV-RP-0591, Redundant Dynamic Positioning Systems with Closed Bus-Ties, April 2024 edition. Applicable within the relevant notation and agreed verification basis; later editions should be checked.

DNV. DNV-RU-SHIP Pt.6 Ch.3 Sec.1, applicable edition.

DNV. DNV-RU-SHIP Pt.6 Ch.3 Sec.2, applicable edition.

American Bureau of Shipping. Guide for Dynamic Positioning Systems, February 2024, Section 3/13. Other Classification Societies and notations have their own provisions.

IEC 61000-4-11:2020, Electromagnetic compatibility (EMC) – Part 4-11: Testing and measurement techniques – Voltage dips, short interruptions and voltage variations immunity tests for equipment with input current up to 16 A per phase.

IEC 61000-4-34, Electromagnetic compatibility (EMC) – Part 4-34: Testing and measurement techniques – Voltage dips, short interruptions and voltage variations immunity tests for equipment with mains current more than 16 A per phase, including applicable amendments.

IEC 61000-4-29:2026, Electromagnetic compatibility (EMC) – Part 4-29: Testing and measurement techniques – Voltage dips, short interruptions and voltage variations on DC input power port immunity tests.

IEC 60050-811, International Electrotechnical Vocabulary – Part 811: Electric traction, IEV 811-29-42, “semiconductor circuit-breaker”.

IEC 60947-2:2024, Low-voltage switchgear and control gear – Part 2: Circuit-breakers.

IEEE C37.111 and IEC 60255-24, Measuring relays and protection equipment – Part 24: Common format for transient data exchange (COMTRADE) for power systems. Relevant to the recording and exchange of test and event data.

Equipment specific OEM documentation supplements the above references for protection devices, converters, drives, sources, batteries, UPS systems and their controls.

16 SUPPORTING EXAMPLES AND LIFECYCLE RESPONSIBILITIES

16.1 HOW TO USE THE EXAMPLES

16.1.1 The examples below show the reasoning that links an attribute to evidence and to continuing verification. They are not test procedures or approved vessel architectures, and the values used are illustrative. The same approach can be used for other voltages, equipment and redundancy arrangements.

16.2 CONTROL POWER AND A FAULTED BRANCH

16.2.1 A 24 V DC supply feeds several control circuits. A fault on one branch may pull down the supply to the healthy branches if the source current limits before the branch protective device operates (see Section 6.12). The intent is to keep the required healthy controls available and to contain the consequence within the redundancy concept.

16.2.2 The basis of confidence should link the source behaviour, the branch protection and the equipment tolerance to the functions actually supplied, and explain the effects on the local subsystem, running generators, thrusters, position and heading. A successful check of the power supply alone does not answer that question.

16.2.3 The attribute is maintained by controlling substitution of sources and protective devices, added loads, wiring changes and cross connections. After a relevant change or event, the owner should review the affected evidence and verify the installed functions before relying on the earlier conclusion.

16.2.4 Figure 16-1 illustrates how a fault on one branch of a 24 V DC distribution group may affect healthy consumers where branch protection and source current-limit behaviour are not adequately coordinated. The verification should establish whether the source, protection and equipment response keep the required healthy functions available during the fault, its clearance and the recovery. The drawing does not imply that redundant DP groups share a control supply.

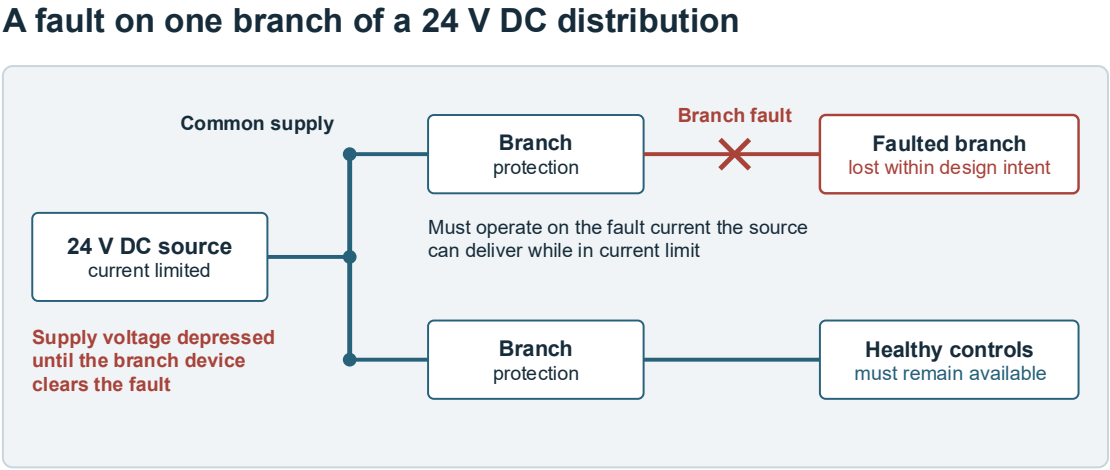


Figure 16-1 Illustrative fault on one branch of a 24 V DC distribution group

16.2.5 Figure 16-2 shows a cross-fed 24 V DC control-power arrangement in which each power supply can feed both distribution buses through separate series blocking diodes. The arrangement can maintain both buses following the loss of one power supply. However, a low-impedance fault on an outgoing branch can demand current from both power supplies through the diode feeds. If the branch protective device does not clear the fault before the power supplies enter current limit, the resulting voltage depression can affect both 24 V DC buses and the healthy consumers in both redundancy groups. Maloperation or loss of control, protection or monitoring functions in both groups could then exceed the worst case failure design intent and result in loss of position. Verification should therefore demonstrate branch-fault discrimination, adequate clearing current and time, power-supply current-limit behaviour, and ride-through of the healthy consumers on both buses.

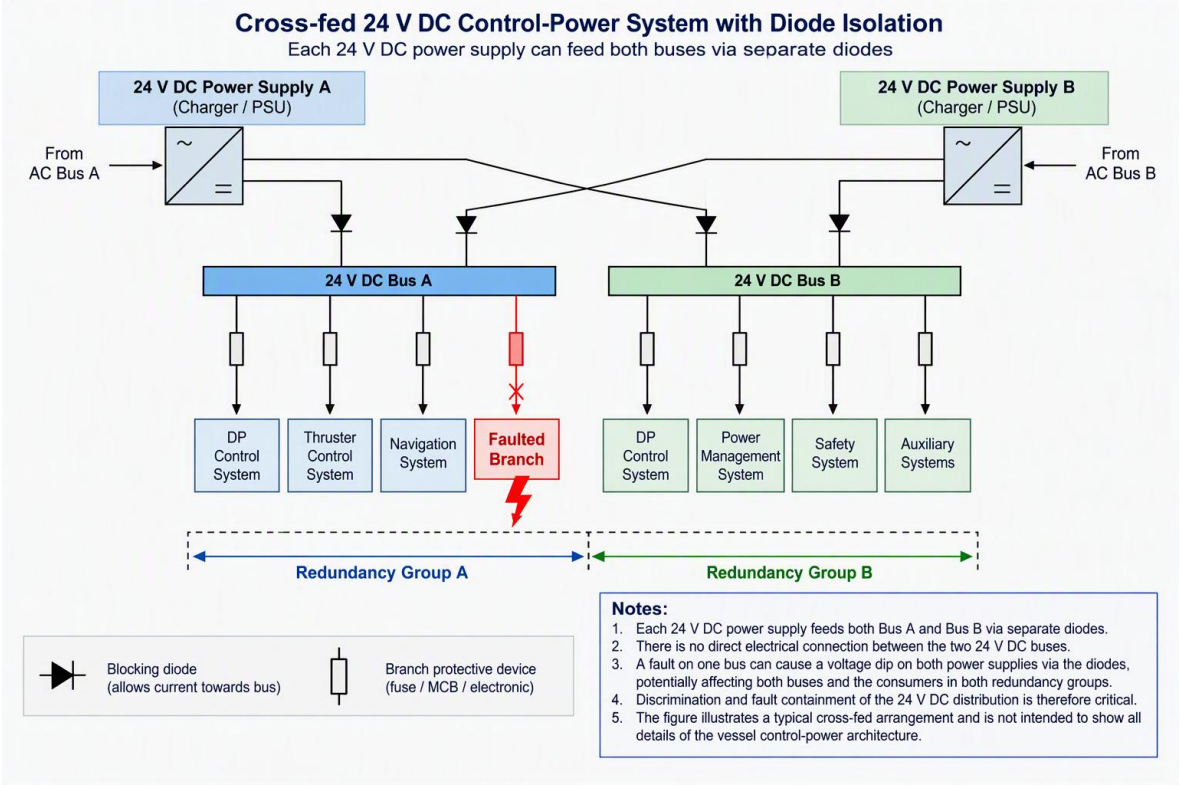


Figure 16-2 Cross-fed 24 V DC control-power system with diode isolation

16.3 AC EQUIPMENT THAT REMAINS ENERGISED

16.3.1 An AC thruster drive may stay energised through a disturbance while the available torque or speed falls. The intent is to maintain the thrust needed from the surviving group, with acceptable control and recovery. An indication that the drive did not trip is useful, and should be supported by evidence of the output actually delivered.

16.3.2 Confidence should be based on the connected drive, motor, controls and supporting services, and on the resulting effect on DP capability. Changes to settings, software and equipment should be reviewed for their effect on that response, and verification should be proportionate to what has changed.

16.4 A CONVERTER USED AS A FAULT BARRIER

16.4.1 A converter transfers power between DC sections and is designed to limit / prevent the transfer of a fault. The intent is to contain the failure while keeping the sources, controls and consumers needed on the healthy section.

16.4.2 The evidence should address the converter topology, the directions of power flow, the relevant failure modes, control supplies, stored energy and any bypass or alternative path. A normal current limiting characteristic is not proof of isolation after a semiconductor or control failure.

16.4.3 The owner should retain the configuration and evidence on which the barrier has been verified and validated. Changes to firmware, protection, cooling, energy storage or bypass arrangements should lead to a review of the affected conclusion. A replacement unit should be checked for equivalence in the characteristics that matter to the barrier, including firmware and settings.

16.5 DERIVING A DISTURBANCE ENVELOPE

16.5.1 This example shows how a disturbance envelope is derived from the protection assessment. The arrangement is a two section 690 V AC system with a closed bus tie, four generators, thrusters supplied through VSDs, and a 440 V auxiliary distribution supplied from a service transformer on each section. The point of use is the coil supply of the contactors feeding thruster auxiliary cooling on the healthy section, supplied from the 440 V distribution. The fault is a three phase fault on a generator feeder on the faulted section.

16.5.2 The envelope is built up from the elements in Table 16-1. On a real vessel each value should come from the vessel's own protection assessment.

Table 16-1 Illustrative derivation of a disturbance envelope

Element	Illustrative value	Source
Protection operating time	40 ms	Relay pickup to trip command, from the protection coordination study for the fault and source combination assessed.
Trip path and breaker time	50 ms	Trip command to contact separation and arc extinction, from the installed device data.
Primary clearance time	90 ms	Sum of the above. Basis for the normal case.
Backup clearance time	390 ms	Primary clearance time plus the required backup or breaker failure action, where the redundancy concept relies on it. The envelope should be derived for this case as well as the normal case.

Element	Illustrative value	Source
Residual voltage at the point of use	25 % of nominal	From the fault study at the 440 V distribution, taking account of the service transformer impedance and the contribution of connected sources.
Recovery profile	Up to 115 % of nominal, settling within 800 ms	AVR response after clearance, including overshoot. Converter fed and DC arrangements should be derived separately.

16.5.3 The resulting envelope at the point of use is a reduction to 25 % of nominal voltage for up to 390 ms, followed by a recovery not exceeding 115 % of nominal and settling within 800 ms. The equipment at that point of use is required to keep its function throughout. If it cannot, the deficiency lies in the design or in the protection performance, and further testing will not resolve it.

16.5.4 The envelope applies to that point of use, fault and source combination only. An envelope should be derived for each point of use at which a required surviving function is delivered, and for the source combinations that are most demanding for each conclusion. The strongest source combination normally gives the greatest equipment duty; the weakest or most current limited combination normally gives the slowest detection and the longest disturbance.

16.5.5 Where immunity information to IEC 61000-4-11, IEC 61000-4-34 or IEC 61000-4-29 is available for the equipment, it can be compared with the envelope (see Section 9.4). A statement of compliance with an immunity class does not on its own show that the required surviving function will be maintained, because it relates to standard test levels and to the equipment as tested.

16.6 SUMMARISING THE EVIDENCE

16.6.1 The evidence supporting the basis of confidence should be presented so that a reviewer can see, for each attribute, which of the four conclusions in Section 4.1 is supported, by what evidence, and what remains open. Table 16-2 illustrates one way of doing this for the arrangement in Section 16.5. A summary in this form is the natural content of the handover described in Section 11.9.

Table 16-2 Illustrative evidence summary

Attribute	Conclusion	Evidence relied upon	Status	Open item and disposition
Selective isolation of a generator feeder fault	2	Protection coordination study; secondary injection of relay functions; primary injection of installed sensing chain	Supported	Interruption at service voltage not demonstrated; covered by device certification and maintenance records.
Thruster drive ride-through, healthy section	1, 4	OEM immunity data; AVR modulation disturbance measured at drive terminals; integrated DP trial at 60 % thruster load	Supported	Not demonstrated above 60 % thruster load; operating limitation recorded.

Attribute	Conclusion	Evidence relied upon	Status	Open item and disposition
Auxiliary contactor ride-through	1	Coil drop out data; disturbance measured at coil supply during the same test	Partial	Backup clearance case (390 ms) not applied; to be closed by analysis or further disturbance testing.
Re-acceleration of the surviving motor group	4	Modelling only	Partial	No measured evidence. Model validated against one recorded event; extension to this case recorded as an assumption.
Arc fault containment, main switchboard	2	Light source functional test; current check by calculation	Partial	Detection under arcing fault current not demonstrated; lowest source combination not assessed.
Control power branch fault containment	1, 2	Discrimination data for the installed device pair; source current limit from OEM	Supported	Valid for the recorded device pairing only; substitution to be controlled.

16.6.2 A gap recorded in this way is not a deficiency. It states the limit of the evidence, so that the owner, the operating team and later reviewers know what has and has not been demonstrated. A gap becomes a problem when it is not recorded, or when a limitation is presented as an equivalence.

16.7 CONFIDENCE THROUGH THE LIFECYCLE

16.7.1 The record should allow a later owner, maintainer or reviewer to understand why the vessel was considered suitable for its intended configuration, what assumptions supported that conclusion and which changes would invalidate it. Figure 16-3 illustrates how the basis of confidence should be maintained through design, construction, commissioning, operation, modification and periodic verification.

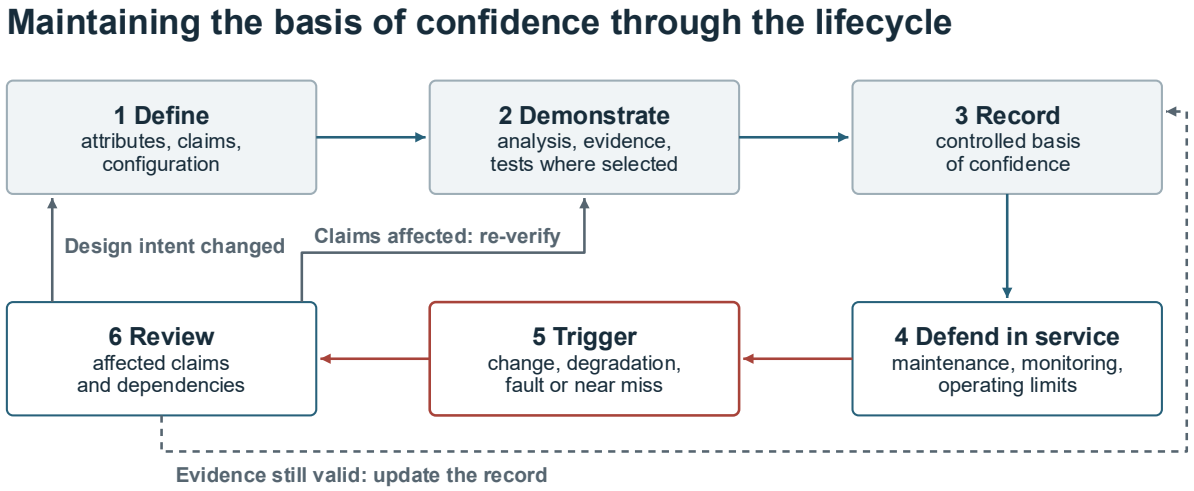


Figure 16-3 Maintaining the basis of confidence through the lifecycle

16.8 STAKEHOLDER RESPONSIBILITIES

16.8.1 Responsibilities should be allocated by the parties involved. Table 16-3 lists typical contributions. It does not transfer the owner's responsibilities or assign approval powers. One organisation may fill several roles, but integration and decision responsibilities should remain clear.

Table 16-3 Typical stakeholder contributions

Stakeholders	Contribution	Guidance intent
MTS DP Committee	Guidance development	Maintain the relationship between guidance, industry learning and the attributes needed for station keeping.
Flag Administration or delegated body	Applicable statutory basis	Identify the applicable requirements and any acceptance required within its authority.
Classification society	Applicable Class basis	Establish notation-specific expectations, evidence and survey requirements within its scope.
Shipyard and system integrator	Design and integration	Coordinate interfaces, commissioning and the handover of evidence that represents the installed system.
Equipment vendor community	Equipment capability and limits	Explain relevant behaviour, fault duty, dependencies, maintenance and changes affecting the evidence.
Consultant community	Analysis and independent review	Connect failure effects, verification evidence and unresolved limits to the redundancy concept.
Training institutions	Competence development	Support understanding of fault propagation, the limits of test methods and the responsibilities of personnel.
Vessel Owners/Operators	Lifecycle ownership	Retain the evidence, allocate resources, control change and establish the basis for operational use.
Vessel management and operational teams	Operation and maintenance	Maintain the required / verified configuration, recognise degradation and report events or changes that challenge the assurance basis.