



**Smart Transformer for Enhanced Efficiency and
Sustainability in Maritime Transportation**

Deliverable 6.1– Report on standardised grid design

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Abstract

Deliverable abstract	
This task defines standardized architecture for the STEESMAT onboard DC microgrid based on the ODCA DC-sector concept. DC sectors and their interconnections are identified to establish a modular and scalable grid structure that enables selective fault isolation, coordinated protection, and efficient system integration. The architecture is further adapted to maritime requirements by addressing load prioritization, redundancy, fault management, and continued operation under degraded conditions. The resulting framework provides a basis for a resilient and highly available onboard DC power system capable of supporting safety-critical vessel functions.	

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1 Introduction

Task T6.1 (M1–M24): Establish the optimal design of the STEESMAT onboard DC power network in compliance with the ODCA specifications. DC sectors will be identified, and their functions, responsibilities, and interconnections with other sectors will be defined.

2 Chapter Terms and Definitions

- **DC Grid:** Electrical power distribution system in which energy sources, storage systems, and loads are interconnected via a common DC distribution network, allowing bidirectional energy exchange.
- **DC Sector:** Functional and protection-related unit consisting of multiple components connected to the DC grid through a common protection device, enabling selective isolation in the event of a fault.
- **Power Supply Unit (PSU / AIC):** Power electronic interface (e.g. Active Infeed Converter) that converts energy from external sources or generators and feeds it into the DC grid in a controlled manner.
- **Consumer:** Electrical loads that draw power from the DC grid. Depending on the converter design, they may also operate bidirectionally and feed energy back into the grid (regenerative operation).
- **Energy Storage System:** Components for temporary storage and release of electrical energy (e.g. batteries, supercapacitors), typically connected to the DC bus via DC/DC converters.
- **Smart Breaker / Protection Device (SSCB):** Electronic switching device (Solid-State Circuit Breaker) for ultra-fast and selective disconnection of DC sectors or components in case of grid faults (e.g. overcurrent or short circuit).
- **DC Bus:** Central low-impedance electrical connection (busbar or cable system) to which all generation, storage, and load branches are connected via power electronic converters.
- **Hierarchical Structure:** Topological arrangement of the DC onboard grid in cascaded levels with graded power and current levels, interconnected through coordinated protection and distribution systems.

3 Maritime System Requirements

3.1 Availability vs. Shutdown

The principle of availability and safe system operation requires that, in maritime environments, the system state "OFF" cannot generally be considered a safe default condition.

A situation-independent decision logic that treats complete system shutdown as a risk-minimizing action is not applicable on a vessel. Instead, each operating condition requires an assessment of which system state results in the lowest overall risk.

In particular, in scenarios where the system is already in a faulted condition and no redundant structures remain available, a complete shutdown must itself be considered safety-critical. The objective of system design is therefore to avoid such situations as far as possible through appropriate architectural and redundancy concepts.

As a consequence, depending on the criticality of the respective system functions, one or more redundant energy supply paths must be provided. These must ensure continued operation of essential functions even under adverse conditions. In particular, safety-critical systems such as navigation, communication, and maneuverability must not be lost even in the event of partial failures.

A total energy loss ("blackout") represents the final and most undesirable escalation stage in a maritime context, as it immediately jeopardizes control of the vessel and may, in extreme cases, require crew evacuation. The system architecture must therefore be consistently designed to prevent such conditions through redundancy, selective fault isolation, and robust operational strategies.

3.2 Continuous Maneuverability Required

Supply of Critical Systems (Mandatory):

- Navigation
- Steering system
- Communication systems
- Fire protection systems

Prioritization of Loads and System Functions

To maintain the maneuverability of a vessel, the main propulsion system and the steering system have the highest priority within the onboard electrical network. These systems are directly safety-critical, as they ensure the controllability of the vessel and are therefore essential for preventing collisions or grounding.

In addition, navigation and communication systems are considered critical functions that must remain fully available even in fault conditions. They not only enable safe positioning but are particularly essential in escalation scenarios to coordinate external assistance and manage emergency situations.

Fire protection systems must also be operated with the highest level of reliability, as they represent the primary means of hazard mitigation in case of fire. Furthermore, signal and navigation lighting must be considered safety-relevant infrastructure, as it ensures visibility and compliance with maritime traffic regulations.

In the case of specialized applications, such as military platforms, defense capability must additionally be classified as a core function with the highest operational priority within the electrical power system.

In addition to these essential functions, further groups of loads exist that can be selectively reduced or disconnected in the event of a fault to release energy and stabilize the overall system. These non-safety-critical loads therefore act as flexible energy buffers and contribute indirectly to ensuring the supply of essential systems. These include in particular:

- Heating and air conditioning systems (operation in reduced mode possible)
- Comfort lighting (excluding emergency lighting)
- Cooling systems outside safety-critical applications
- Galley and catering facilities
- Entertainment and information systems
- Auxiliary consumer network for non-critical end users (e.g. sockets, service outlets, USB interfaces)

The targeted and staged reduction of these loads enables adaptive load management, ensuring system stability even under constrained operating conditions. A prerequisite for this is a clear classification of loads and their proper integration into the energy management and control strategy of the DC system.

4 Load Classification

Class A (always active) — Safety-critical loads

- Navigation
- Steering system
- Communication systems
- Fire protection systems
- Emergency lighting and evacuation systems
- Safety systems

Class A technical areas:

- Bridge
- Engine room

- Control systems

Class B (reducible) — Operational loads These loads are required for basic vessel operation but can be reduced to a limited extent.

- General lighting
- Minimum operation of ventilation and air conditioning systems
- Control and automation systems outside core safety functions

Class C (reducible / disconnectable) — Comfort loads

- Hotel services
- Entertainment systems
- Cooling systems (temporarily disconnectable)
- Socket loads (e.g. hair dryers, chargers)
- Entertainment systems, USB supplies, and IT peripherals
- Lighting outside emergency operation
- Heating and HVAC systems
- Parts of the galley outside critical operation phases

5 Safety vs. Availability Trade-Off

Selective Fault Isolation: a key design principle of maritime DC grids is the selective disconnection of faults. The objective is to isolate the affected network area to the smallest possible segment in order to ensure continued operation of the overall system.

Fault handling must be designed such that only the affected DC sector is disconnected, while all remaining network sections continue to be supplied. Non-selective disconnection (e.g. due to voltage collapse or cascading effects) is not acceptable in maritime systems, as it may compromise vessel maneuverability and safety-critical functions.

For higher-level systems, a redundant design is therefore required, allowing the affected supply area to be taken over by parallel or physically separated network structures (e.g. port/starboard buses). This leads to the necessity of clearly defined network segmentation and a coordinated protection strategy, ensuring both fast fault isolation and voltage stability in the remaining system. No global shutdown.

6 Redundancy Requirements

Redundancy requirements in maritime DC systems exceed classical approaches such as N+1. While N+1 redundancy is often considered sufficient to increase availability in land-based applications, this concept alone is not adequate in the maritime environment.

For safety-critical systems (Class A), the system design must ensure that even in the event of multiple component or supply-level failures, no total loss of functionality occurs. The objective is that, even under multiple fault conditions, a reduced but still safe and controllable operation can be maintained. A complete failure of these systems is not acceptable, as it would directly compromise vessel maneuverability and thus overall safety.

This leads to the need for a multi-level redundancy strategy that goes beyond simple parallelization:

- Physical separation of supply paths
- Functional redundancy at system level
- Segmentation of the network into independent zones
- Staged power reduction instead of shutdown, enabling continued operation of critical systems even under limited energy conditions

For Class A systems, this means that the failure of individual components or entire supply branches shall generally not lead to a loss of functionality, but at most to a minor reduction in performance.

Redundancy must therefore be understood as an integral part of the network architecture and closely coordinated with topology, protection strategy, and load management. Only through this holistic approach can the required high level of availability under maritime operating conditions be achieved.

For the redundant design of safety-critical Class A systems, the following aspects must be considered:

The failure or degradation of system performance must be detected at an early stage. Switching in an emergency to a redundant system that is already weakened or degraded does not provide sufficient safety. Therefore, strategies must be implemented to monitor the state of health (SoH) of the systems.

This can be achieved through appropriate operational strategies, for example by alternating the use of systems so that one operates while the other remains available as redundancy. Alternatively, self-test or diagnostic functions as well as model-based approaches may be used to continuously evaluate system aging.

Operational strategies that distribute the load equally (50:50) between systems to reduce aging effects should be applied with caution. Two systems with identical SoH may, in the event of a failure, cause the remaining unit to fail immediately under 100% load. The same applies to alternating 100% operation if both systems have accumulated equal operating time. In this case, however, the risk is lower, as no additional load increase occurs.

To reduce aging through load distribution, it is advisable to operate the reserve system at a lower load level (e.g. approximately 1/3), while the primary system carries the remaining load (approximately 2/3). This results in the reserve system maintaining a better SoH and reduces the risk of immediate failure under emergency conditions.

For performance diagnostics, each system should be operated at 100% load at defined intervals. In alternating operation, a similar approach can be applied, where the primary system operates at 100% load for approximately 2/3 of the time, while the reserve unit is used for the remaining 1/3. An additional redundant supply unit may be implemented for less critical loads. A full (100%) takeover of Class A loads during diagnostic operation would restrict non-critical consumers, which may not be acceptable outside emergency conditions. Such load cases should therefore be emulated by assigning a partial share of Class A loads to this unit in order to reach full load conditions. Continuous monitoring of this system and its SoH is essential to ensure reliability in emergency situations.

7 Behavior Under Fault Conditions

- **Continued operation under single fault conditions:** The system must be designed in a modular way such that a single fault does not lead to a system failure.
- **Rapid fault isolation:** Faults must be detected at an early stage to prevent impacts on the higher-level system. Diagnostic functions should identify and clearly indicate single faults to enable fast corrective action.
- **Prevention of fault propagation:** Faults (e.g. undervoltage conditions) must not lead to unacceptable voltage levels in unaffected parts of the network in order to avoid cascading failures.
- **Selectivity of protection mechanisms:** Protection functions must be designed such that, in the event of a fault, only the smallest affected network segment is disconnected in order to maximize system availability.
- **Defined fail-safe states:** For all relevant fault conditions, well-defined safe states must be specified, to which the system can transition in a controlled manner.

8 Advanced Requirements for DC Systems

- No mechanical inertia (DC-specific)
- High control dynamics required
- Loads must tolerate transient voltage dips
- **Asymmetric tolerance strategy (extended ranges on load side)**
 - Sources more stable
 - Loads more robust

9 Basic Structure of a DC Grid

Oversizing must be consistently avoided on ships, even more so than in land-based installations, as in addition to installation costs, space constraints and reduced payload play a decisive role.

Ensuring high safety and availability under these constraints represents a significant challenge. This can be addressed, among other approaches, through increased system intelligence, enhanced diagnostic capabilities (e.g. aging models), and well-designed system architectures with a high degree of flexibility.

For intelligent load management, communication with a central management module is generally feasible on ships due to their limited physical size. However, due to redundancy requirements, Class A functions must at all times be capable of maintaining basic operation independently of any central load management system.

This leads to the principle of a redundant design with locally implemented core functions, supplemented by communication-based efficiency optimization. In the event of communication failure within the technical system network, the additional power required due to reduced efficiency can be compensated by load reduction in other areas, if necessary through targeted derating.

10 Topologies for DC Grids

- **Bus topology:** A central bus, optionally implemented redundantly as two parallel DC buses. If one bus fails or is interrupted, the second bus must take over the load.
- **Ring topology:** In practical ship installations, this corresponds to two parallel buses whose ends are interconnected. In the event of a fault, only the shorter supply path may be affected. An advantage is that no switching with operational interruption is required during fault conditions.
- **Tree topology:** The network branches from a central point into multiple feeders. If a fault occurs in one branch, other branches remain unaffected; however, all loads downstream of the fault are disconnected. Redundant branches for Class A loads can ensure continued supply. The main advantage is reduced material usage compared to bus or ring structures, resulting in lower cost, weight, and installation space. The disadvantage is reduced redundancy and fault tolerance, and strong centralization implies that a fault at the central node may affect the entire network.
- **Hybrid topologies:** In practice, these represent the most common implementation. The main supply — being the critical point in a tree structure — is typically realized as a redundant bus or ring topology. Sub-distribution levels are usually implemented as tree structures. Class A loads are supplied via redundant tree structures from different bus or ring sections. Comfort loads are typically connected via simple tree structures, either to a single bus or distributed across multiple buses, where redundancy is not necessarily required.

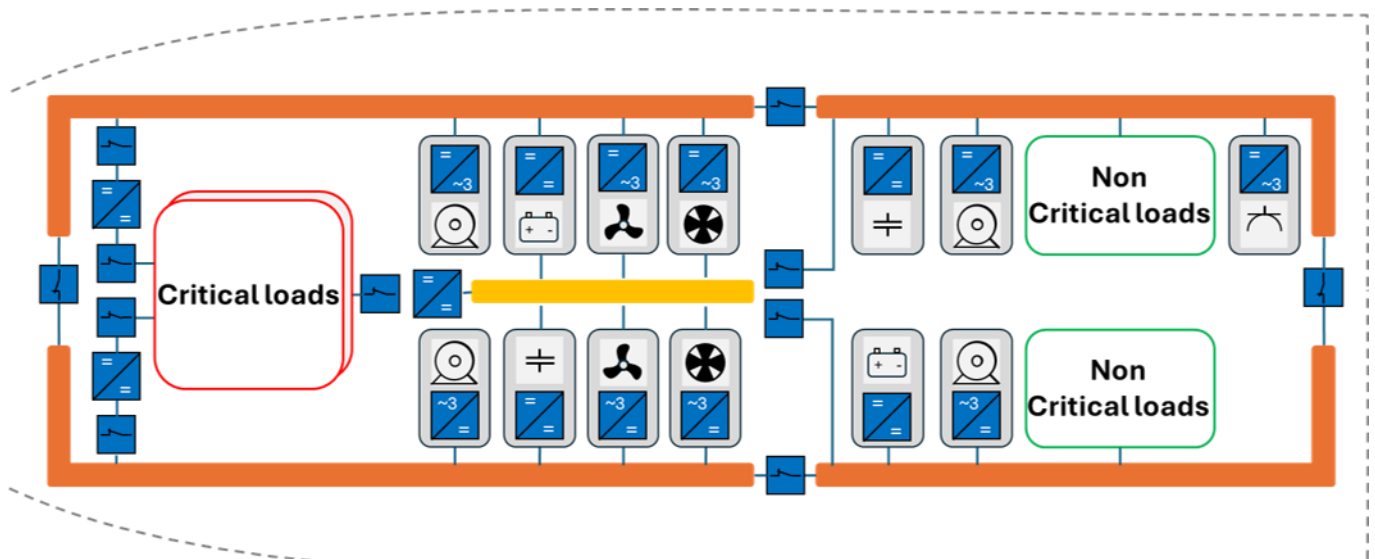


figure 1 — Example Topology: Ring Structure

The main distribution is implemented as a ring-shaped DC bus with multiple switching points for selective segmentation and fault isolation. Critical loads are internally realized using a hybrid topology and are supplied redundantly from different sections of the bus.

Non-critical loads are integrated via simple tree structures or hybrid configurations with non-redundant bus connections. The central DC/DC converter, serving as a second level of redundancy, can be supplied either from one of the non-critical networks or, depending on the power rating, from both networks in parallel.

In contrast to conventional AC systems, where sources and loads are often directly interconnected, all components in a DC onboard grid are connected via power electronic converters. This so-called converter coupling represents a key architectural principle and enables active control of power flow as well as defined system behavior under fault conditions.

By interposing DC/DC and AC/DC converters, electrical quantities such as voltage and current are not passively determined by the network, but are actively regulated by the respective converters. This allows decoupling of individual network segments and targeted adaptation to differing requirements of sources and loads.

11 Consideration of Different Maritime Applications

11.1 Container Vessels

- **High share of continuous loads:** Particularly propulsion systems represent a dominant and largely steady load.
- **Predictable load profiles:** Loads are largely predictable, as route and operational profiles are known in advance. The energy demand of consumers can be forecast reliably over the course of a day.
- **Flexible handling of non-critical loads:** Non-critical loads can be shifted in time or temporarily reduced. For example, short-term interruptions of reefer containers (e.g. at night for limited periods) are generally non-critical and do not directly impact operation.
- **Climate-dependent cooling demand:** Cooling energy demand is known and depends on ambient conditions; it can be optimized through flexible load management.
- **Relatively robust loads:** Many consumers are tolerant to variations and temporary deviations from nominal conditions.

11.2 Cruise Ships — Typical Characteristics

- **Completely different load profile:** Characterized by a large number of sensitive consumers, particularly hotel systems.
- **Limited predictability of load management:** Although certain time patterns exist (e.g. meal times or port stays), there is no direct control over simultaneous load activation driven by passenger behavior. Load peaks are therefore triggered by external factors and can only be managed to a limited extent.
- **Very high share of sensitive loads:** Hospitality systems require stable operation and are less tolerant to disruptions or deviations.
- **Limited flexibility for load reduction:** Load reduction or temporal shifting is generally not acceptable under normal operating conditions, as it directly impacts passenger comfort and user experience.

Conclusion: Compared to cargo vessels, the available flexibility for load-side optimization during normal operation is significantly reduced.

11.3 IT / Communication Systems — Typical Characteristics

- **Very high requirements for availability and bandwidth:** As a large number of passengers simultaneously use communication and entertainment services, systems must support high concurrency.
- **Strong dependency on user behavior:** Usage is highly driven by passenger activity and can only be predicted to a limited extent.

- **Load peaks driven by external factors:** Peak loads typically occur at defined times (e.g. mornings, evenings, sea days), but cannot be actively controlled or reduced.
- **Limited acceptability of service restriction:** Reducing or limiting services is generally not acceptable under normal operating conditions, as it directly impacts customer satisfaction.

11.4 Medical Systems on Cruise Ships — Typical Characteristics

- **High requirements for availability, reliability, and immediate readiness:** Medical systems are safety-critical and must be fully operational without delay when required.
- **Low baseline load with high dynamic demand:** Under normal operation, power demand is relatively low and stable; however, it may increase significantly and rapidly during active use.
- **Unpredictable load behavior:** These loads cannot be planned and must be fully available at all times.

No allowable load reduction or shifting (with exceptions): In principle, load reduction or shifting is not acceptable. However, a distinction must be made between critical and non-time-critical medical applications.

- Life-support systems (e.g. intensive care) must always remain fully available and have highest priority.
- Less time-critical applications (e.g. diagnostic systems such as X-ray) may be delayed under emergency conditions without immediately compromising patient safety.
- **Internal prioritization required:** The system design must include clear prioritization within medical loads, combined with appropriate redundancy and preferential supply of critical functions.

Conclusion: Many medical applications require systems to handle high, non-controllable dynamics and simultaneous load peaks.

12 Component Overview and System Comparison

- **Sources:** Energy generation systems (e.g. diesel or gas turbine generator sets, fuel cells), typically interfaced via power electronic AC/DC or DC/DC converters and feeding the DC bus in a controlled manner.
- **Storage:** Energy storage systems (e.g. battery systems, supercapacitors) used for steady-state power supply, buffering of load variations, and providing system reserves in fault conditions; continuously connected in a bidirectional manner.
- **Loads:** Electrical consumers with widely varying priority levels (Class A to C) and dynamic behavior. Certain high-power loads (e.g. main propulsion systems, winches) may temporarily operate bidirectionally to reduce net energy demand through regenerative operation.
- **Protection devices:** Fast electronic or hybrid DC switching devices (SSCBs) for selective isolation of faulted network sections, preventing unacceptable system voltage drops and widespread network failures.
- **Cabling:** Power and signal cabling with increased requirements for insulation strength, current-carrying capacity, and mechanical robustness. Unlike AC systems, the skin effect does not represent a dominant factor for the effective conductor cross-section in steady-state operation. High requirements apply for insulation performance, environmental resistance, and mechanical stability under vibration.

13 Environmental Conditions

Environmental conditions in maritime applications differ significantly from land-based systems, particularly with regard to corrosion, humidity, vibration, and temperature dynamics.

13.1 Salt and Humidity Effects in Maritime Environments

Environmental conditions at sea are characterized in particular by high humidity combined with a salt-laden atmosphere. These factors are highly corrosive and impose significant requirements on electrical components as well as on the insulation systems used.

For AC systems, established test methods and qualification standards exist that account for such conditions. However, the results obtained from these cannot be directly transferred to DC systems, as DC applications exhibit additional and partly different aging and failure mechanisms.

In particular, moisture and salt in DC operation lead to effects such as electrolytic migration, leakage currents, and accelerated degradation of insulation materials. These mechanisms can result in long-term insulation failures, whose characteristics and temporal behavior differ significantly from those observed in AC systems.

Therefore, dedicated investigation and evaluation of insulation systems — previously primarily used in land-based DC applications — are required under maritime operating conditions. A direct transfer of existing maritime AC qualifications or land-based DC approvals is not sufficient and may lead to incorrect assessments of system reliability.

13.2 Vibration and Mechanical Stress in Maritime Environments

In maritime applications, electrical systems are continuously exposed to mechanical stresses that differ significantly from land-based installations. In addition to continuous vibrations from propulsion systems, generators, and auxiliary equipment, additional excitations arise from wave motion and the structural natural frequencies of the ship hull.

Compared to stationary land-based systems, the frequency spectrum of these vibrations is broader and includes both low-frequency movements caused by ship motion (typically < 1 Hz) as well as high-frequency excitations from rotating machinery and power electronics (ranging from several Hz up to the kHz range). These overlapping effects result in complex mechanical loads on components, connection elements, and conductor structures.

In addition to vibration, continuous changes in vessel position (roll and pitch) must be considered. These lead to varying mechanical stresses on components, cables, and mountings, as well as dynamic loading of connectors and contact points. Unlike land-based installations, systems are therefore subject not only to vibrations but also to quasi-static positional changes and accelerations.

These conditions result in specific challenges for electrical systems, particularly with respect to the mechanical stability of connections, the long-term reliability of connectors, and the integrity of insulation systems under combined mechanical and environmental stress. Bolted connections, connector systems, and conductor fixations must therefore be appropriately dimensioned and secured against loosening, contact degradation, and material fatigue.

Consequently, a dedicated design and qualification of electrical components under maritime vibration and motion conditions is required. Test and qualification results from land-based applications are only partially transferable and must be complemented by application-specific test profiles.

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