D5.2 Market readiness level of different storage solutions and the next steps to increase the TRL – update

Interfaces requirements between the new products and on-board systems

Document Identification			
Status	Final	**Due Date**	31st of May 2025
Version	1.0	**Submission Date**	28th of May 2025

Related WP	5	**Document Reference**	D5.2
Related Deliverables	D2.3, D2.4, D5.3	**Dissemination Level**	PU
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Keywords
Interface requirements, standardisation, mechanical integration, electrical integration, safety, control system integration

Funded by the European Union

V-ACCESS; Grant agreement ID: 101096831

Table of Contents

List of Figures

List of Tables

Acronyms

- SC - SuperCapacitors
- SMES - Superconducting Magnetic Energy Storage
- ESS - Energy Storage System
- BESS - Battery Energy Storage System
- OSV - Offshore Service Vessel
- AHC - Active Heave Compensation
- PID - Public Interest Disclosure
- HMI - Human Machine Interface
- EMS - Energy Management System
- SoC - State of Charge
- DG - Diesel Generator
- SFOC - Specific Fuel Oil Curve
- AFE - Active Front End
- PCS - Power Conditioning System
- TRL - Technology Readiness Level
- EMC - Electromagnetic Compatibility

1 Introduction

This report is about interfaces requirements between the new products - SC and SMES - and the standardization of the solutions when integrating SC and SMES onboard the 3 vessel types identified in WP1:

- Case: Fully Electric Ferry (electric ferry)
- Case: Offshore Supply Vessel – Active Heave Compensation (OSV-AHC)
- Case: Trawler

These 3 cases were selected in WP1 because they were among the 6 most promising ones due to power requirements and the fact that one of the project partners (VARD) were able to provide log data and most of the design documentation needed in the project for these 3 vessel types.

This report contains a structured description of how to integrate SC (chapter 2) and SMES (chapter 3) into these 3 cases. These chapters for SC and SMES have the same structure:

1. General description of the technology and the concept designs for the 3 cases.
2. Mechanical integration in the 3 cases.
3. Electrical integration in the 3 cases.
4. Safety.

Chapter 4 is about how to integrate the new ESS with SC and SMES into the control system onboard the vessel.

The following in this chapter is a further description of the 3 cases selected to be studied.

1.1 Case: Fully Electric Ferry (Electric Ferry)

The single line below shows an example of a fully electric ferry utilizing a DC power system. The diesel generators are for emergency use and are NOT used in normal operation.

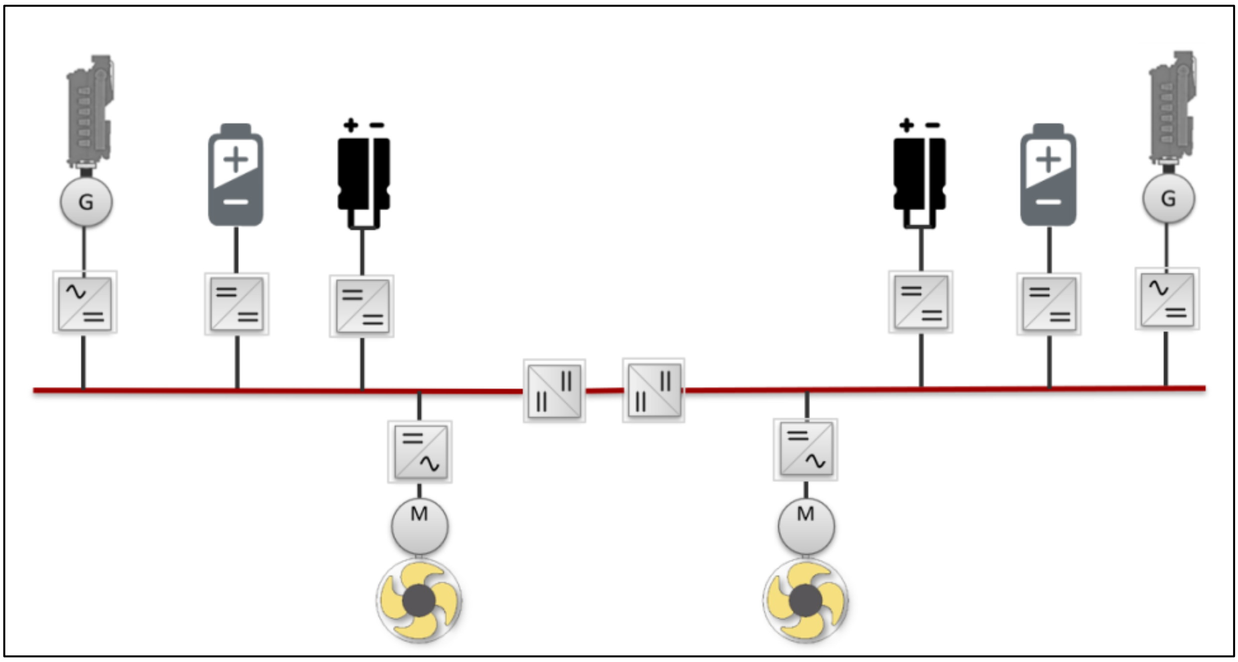

Figure 1: Electrical single line sketch for case Electric Ferry

Typical operation patterns for the electric ferry are:

Acceleration Phase:

- Power Demand: High
- During acceleration, the ferry moves from a stationary or low-speed state to its cruising speed. This requires a significant increase in power

Transit Phase:

- Power Demand: Medium/high
- Once the ferry reaches its cruising speed, the power consumption remains steady, though it may vary slightly due to factors like wind, currents, and waves.

Deceleration Phase:

- Power Demand: Low
- As the vessel approaches its destination it begins to slow down. During this phase, power consumption is reduced as the vessel gradually decelerates.

Manoeuvring Phase (Docking/Undocking):

- Power Demand: Variable, but can be High
- Manoeuvring, such as docking, undocking, or navigating narrow passages, requires precise control over the ferry's movements. This phase often involves changes in thrust direction, low-speed operations, and frequent adjustments.
- Power demand can be high at times due to the frequent adjustments in speed and direction.

In the V-ACCESS project the idea for the fully electric ferry case is to use ESS's with SC/SMES in addition to the existing BESS to extend the lifetime of the batteries. If the lifetime of the batteries is extended the total battery cost in the vessel's lifetime can be reduced.

1.2 Case: Offshore Supply Vessel – Active Heave Compensation (OSV-AHC)

The single line below shows an example of a Service Operation Vessel (SOV) utilizing a DC power system. This vessel has a hybrid power system using diesel generators and electric power for ESS’s.

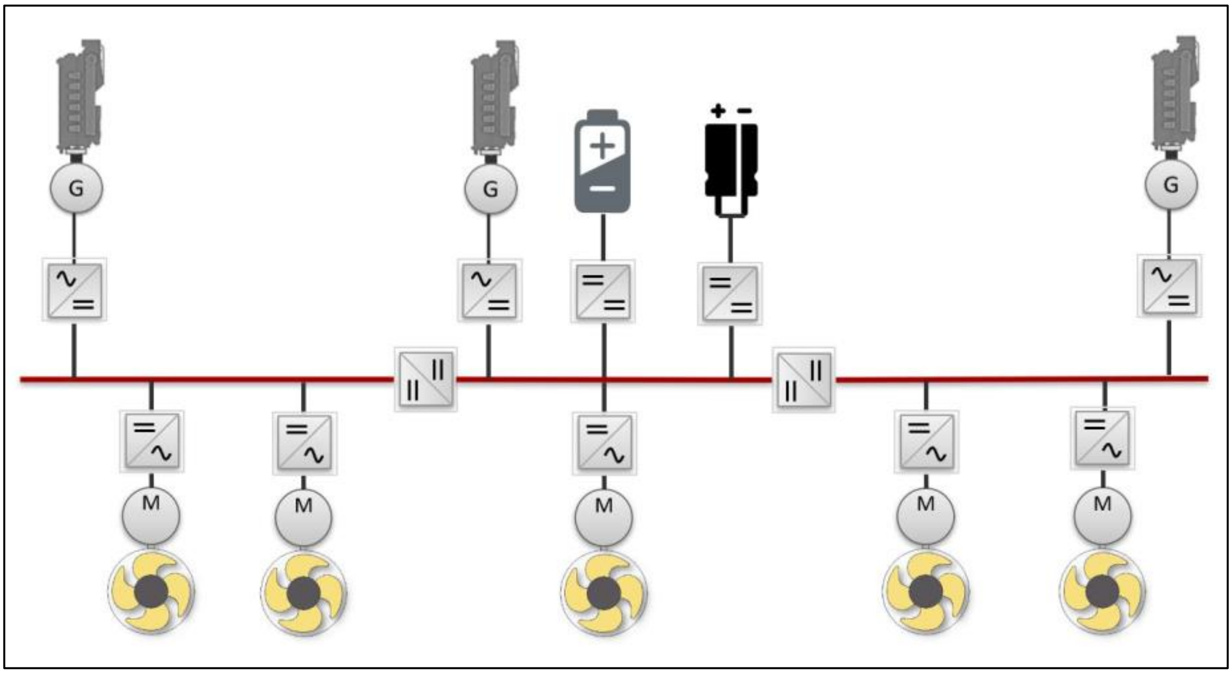

Figure 2: Electrical single line sketch for case OSC-AHC

Typical operation patterns are:

<u>Dynamic Positioning (DP) Operations:</u>

- Power Demand: Variable (low/medium/high)
- Dynamic positioning is a system that allows the SOV to maintain a fixed position at sea, often in challenging conditions (e.g., strong winds, currents, and waves) without the use of anchors.
- The vessel's thrusters and propulsion systems are actively controlled by the DP system to counteract environmental forces and maintain precise positioning. This process requires significant and fluctuating amounts of power as the system continually adjusts to varying sea conditions.

- The power consumption during DP can vary depending on factors like sea state, wind speed, and currents, with power peaking during rough weather when the vessel needs more force to remain stable.

Walk-to-Work (W2W) Operations:

- Power Demand: Variable (medium).
- Walk-to-work operations involve using a motion-compensated gangway to transfer technicians and equipment safely between the SOV and offshore structures like wind turbines or oil platforms.
- During this phase, the SOV may still operate in dynamic positioning mode, as it needs to stay in position relative to the offshore structure. However, the power demand here can be lower compared to full DP operations, as precise positioning may be focused more on safety rather than exact station-keeping.
- The power demand fluctuates based on gangway operation and the need to maintain the position of the vessel.

Transit Phase:

- Power Demand: Medium/high.
- Once the vessel reaches its cruising speed, the power consumption remains steady, though it may vary slightly due to factors like wind, currents, and waves.

The OSV–AHC case is a hybrid power solution with diesel generators and BESS used to shave the load peaks and operate the generators at more optimum load (“peak shaving”) and to take a generator offline and use the BESS for reverse power (“spinning reserve”) in DP mode.

In the V-ACCESS project the idea in the OSV-AHC case is to use ESS’s with SC/SMES to handle the power peaks in OSV-AHC operations.

1.3 Case: Trawler

The Trawler case is a hybrid power solution with diesel generators and ESS. The single line below shows an example of a stern trawler utilizing a hybrid AC/DC power system combined with mechanical propulsion.

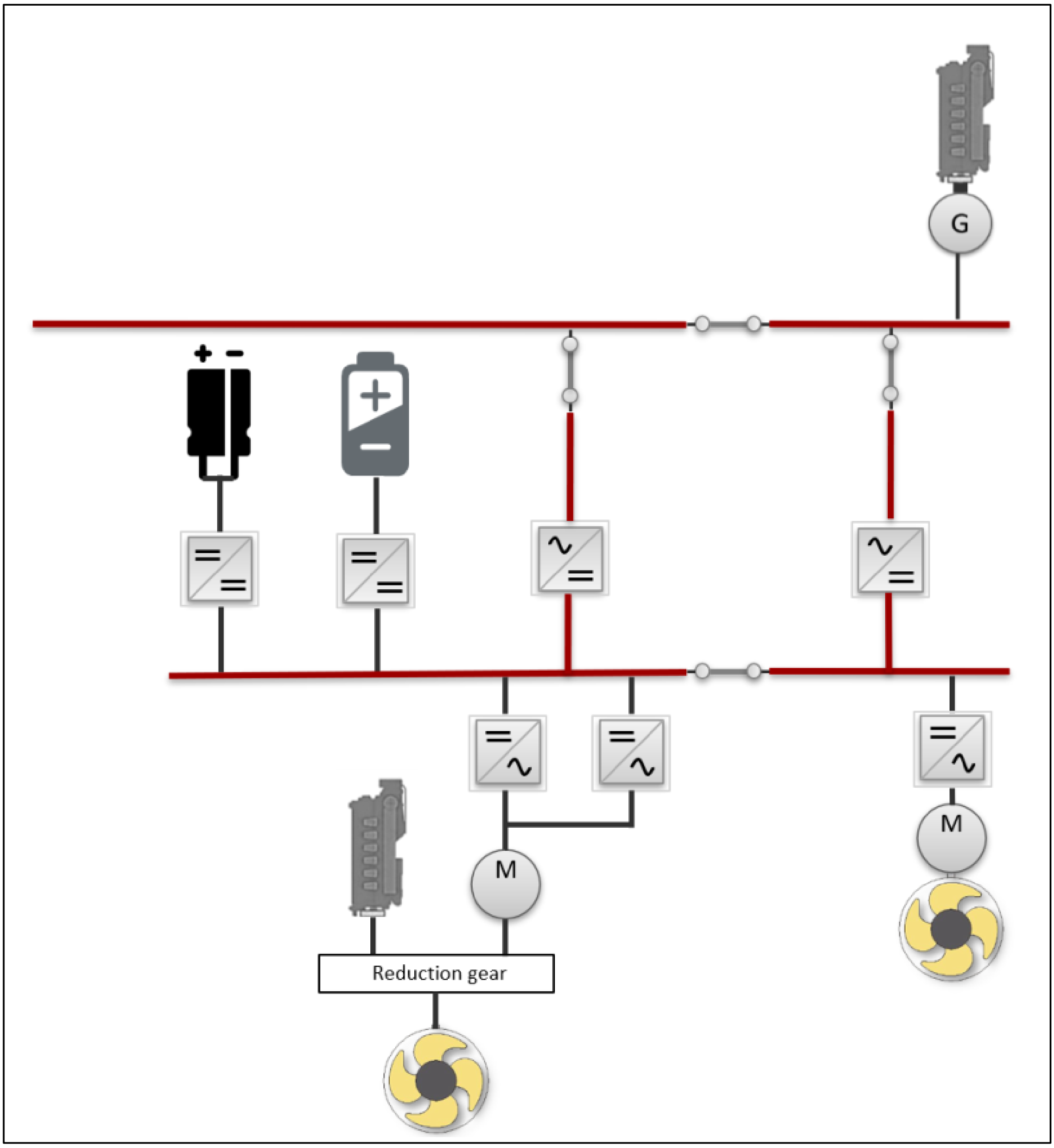

Figure 3: Electrical single line sketch for case Trawler

Typical operation patterns are:

Heaving and Shooting the Winches:

- Power Demand: Variable (Medium to High).
- Shooting refers to the process of deploying the trawl net into the water, while heaving involves retrieving the net, back onto the deck. Both operations require the use of winches, which drive the cables that control the net.
- Power consumption during these phases is significant but varies depending on the depth of the trawl, the size of the net, and the weight of the catch.
- Shooting causes the electric winches to regenerate power as the winches are generally working with gravity when lowering the net.
- Heaving demands more power, especially when lifting heavy loads of fish or operating in deeper waters, where more force is required to pull the net back to the surface.

Trawling:

- Power Demand: Variable (High).
- During trawling, the vessel tows the trawl net behind it through the water, a process that requires considerable power from both the propulsion system and the winches maintaining the net's tension and position.
- Additional power is also consumed by the winches, as they continuously adjust the tension of the trawl warps to ensure proper net positioning and maintain optimal trawling performance.

Transit Phase:

- Power Demand: Medium/high.
- Once the vessel reaches its cruising speed, the power consumption remains steady, though it may vary slightly due to factors like wind, currents, and waves.

The idea in the trawler case is to use ESS's with SC/SMES to extend the lifetime of the batteries in the BESS. If the lifetime of the batteries is extended the total battery cost in the vessel's lifetime can be reduced.

Type of operation:	**Case: Electric Ferry**	**Case: OSV-AHC**	**Case: Trawler**
Acceleration phase:	Power demand: High	n/a	n/a
Transit phase:	Power demand: Medium/high	Power demand: Medium/high	Power demand: Medium/high
Deceleration phase:	Power demand: Low	n/a	n/a
Manoeuvring phase (docking/undocking):	Power demand: Variable, can be high	n/a	n/a
Dynamic Positioning (DP):	n/a	Power demand: Variable (low/medium/high)	n/a
Walk-to-Work (W2W):	n/a	Power demand: Variable (medium)	n/a
Heaving and shooting the winches/trawl:	n/a	n/a	Power demand: Variable (medium to high)
Trawling:	n/a	n/a	Power demand: Variable (high)

Table 1: Summary of power demands for different type of operations in the 3 vessel cases

2 Integrating SuperCapacitors (SC)

The standardization of integration of SC onboard vessels assumes the solution is type approved for marine usage. The rules compliance matrix for SC below shows that the SC from Skeleton is compliant with some of the rules applicable but not all at the time when this report was prepared. The SC from Skeleton used in this project was at TRL 5 at the beginning of the project.

Standards/Rules for SuperCapacitors	Applicable	Compliant	To be compliant	Comment
a. IEC 62391-1 Fixed electric double-layer capacitors for use in electric and electronic equipment – Part 1: Generic specification	Y	N	Y	Cells are being tested during development
b. IEC 62391-2 Fixed electric double-layer capacitors for use in electronic equipment – Part 2: Sectional specification – Electric double layer capacitors for power application	Y	N	Y	
c. IEC 62391-2-1 Fixed electric double-layer capacitors for use in electronic equipment – Part 2-1: Blank detail specification – Electric double-layer capacitors for power application – Assessment level EZ	Y	N	Y	
d. IEC 62576 Electric double-layer capacitors for use in hybrid electric vehicles – Test methods for electrical characteristics	N			
e. IEC 60812 Analysis techniques for system reliability - Procedure for failure mode and effects analysis (FMEA)	Y	N	N	Skeleton has been following alternative AIAG/VDA FMEA guideline
f. UL 810A: Standard for Electrochemical Capacitors	Y	N	Y	Applicable for Skeleton supercapacitor cell and 162V

				module. Also, for one cell type that compliance is achieved and certificate available
g. NFPA 70: National Electrical Code 2017: Article 706 Energy Storage Systems	N			
h. IEC 60068-2-27:2008 Environmental testing - Part 2-27: Tests - Test Ea and guidance: Shock	Y	Y		Also applicable for supercapacitor cells where one product series that has passed
i. ISO 16750-3:2023 Road vehicles — Environmental conditions and testing for electrical and electronic equipment — Part 3: Mechanical loads	N	Y	*	Skeleton has carried out random vibration, sinus vibration and shock test according to this standard for different modules and supercapacitor cells.
j. IEC 62933 Series - Electrical energy storage (EES) systems	N			
k. IEC 60533:2015 Electrical and electronic installations in ships - Electromagnetic compatibility (EMC) - Ships with a metallic hull	N			Skeleton has been focusing on similar DNV marine standards such as

				DNV-RU-SHIP pt.1, 2, 4 and pt. 6.
l. EN55011 Industrial, scientific and medical equipment. Radio-frequency disturbance characteristics. Limits and methods of measurement	N			
m. IEEE Guide for Design, Operation, and Maintenance of Battery Energy Storage Systems, both Stationary and Mobile, and Applications Integrated with Electric Power Systems	N			
n. ABS Requirements for Use of Supercapacitors in the Marine and Offshore Industries	N			

Table 2: Rules compliance matrix for SC

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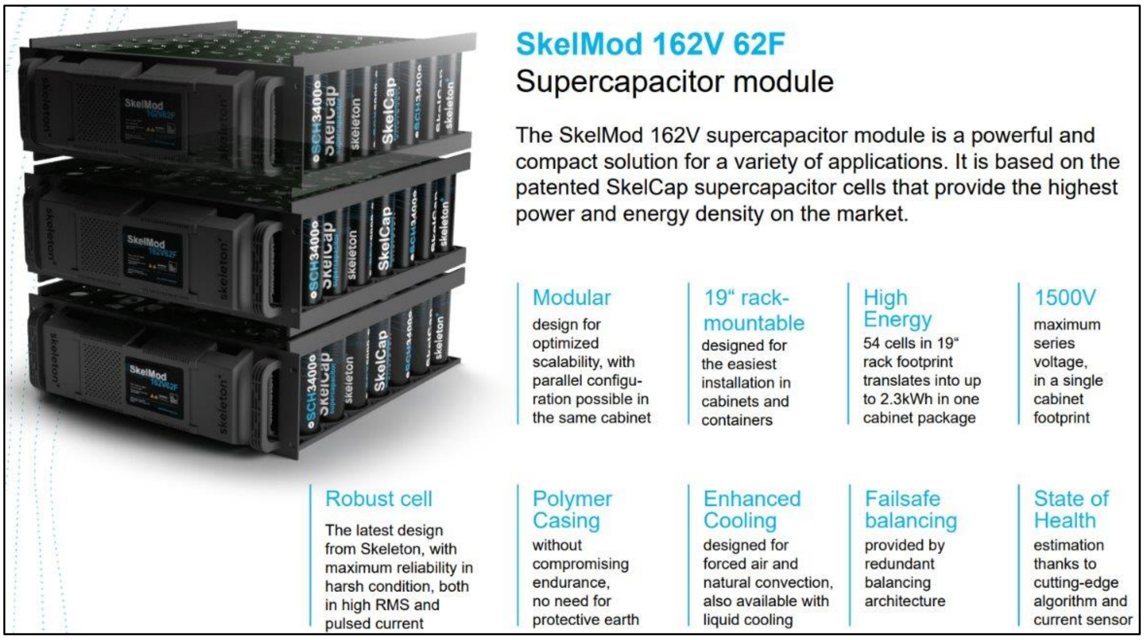
2.1 General description of SC



SkelMod 162V 62F
Supercapacitor module

The SkelMod 162V supercapacitor module is a powerful and compact solution for a variety of applications. It is based on the patented SkelCap supercapacitor cells that provide the highest power and energy density on the market.

Modular
design for optimized scalability, with parallel configuration possible in the same cabinet

19" rack-mountable
designed for the easiest installation in cabinets and containers

High Energy
54 cells in 19" rack footprint translates into up to 2.3kWh in one cabinet package

1500V
maximum series voltage, in a single cabinet footprint

Robust cell
The latest design from Skeleton, with maximum reliability in harsh condition, both in high RMS and pulsed current

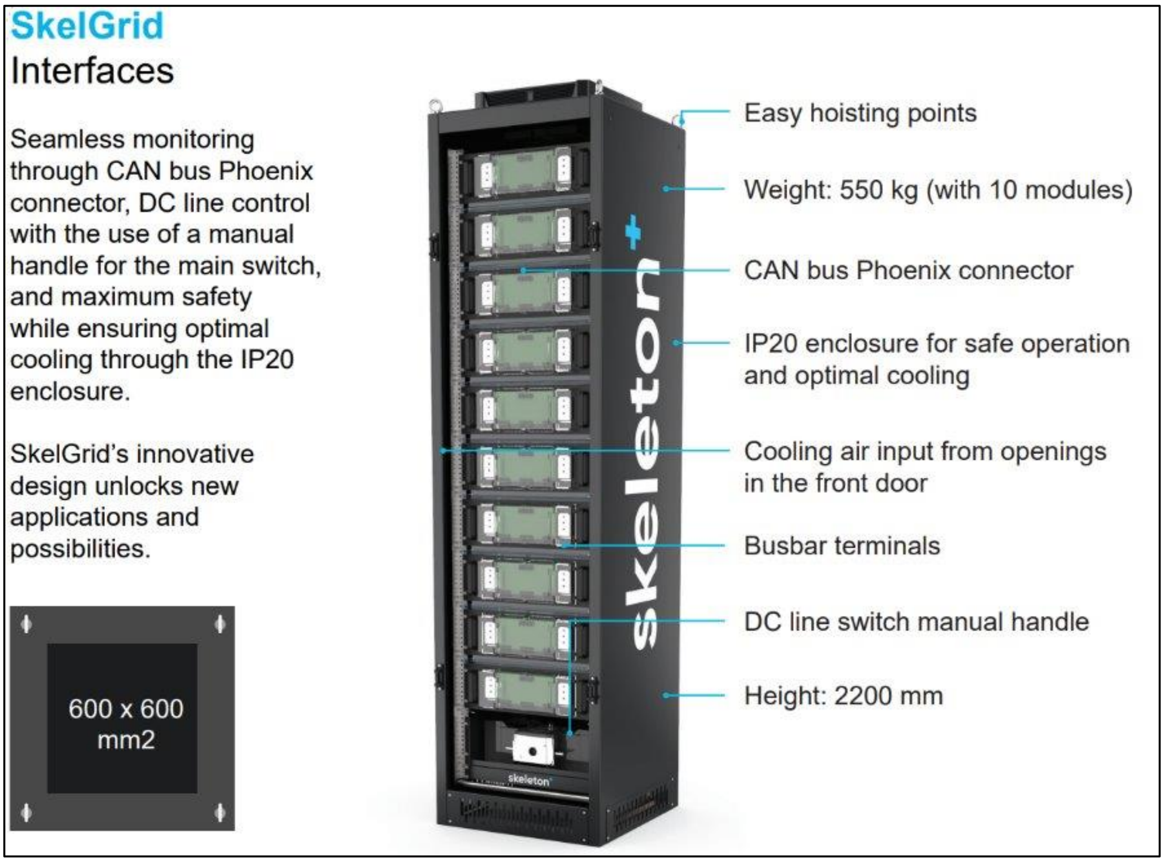
Polymer Casing
without compromising endurance, no need for protective earth

Enhanced Cooling
designed for forced air and natural convection, also available with liquid cooling

Failsafe balancing
provided by redundant balancing architecture

State of Health
estimation thanks to cutting-edge algorithm and current sensor

Figure 4: SkelMod Supercapacitor modules from Skeleton



SkelGrid
Interfaces

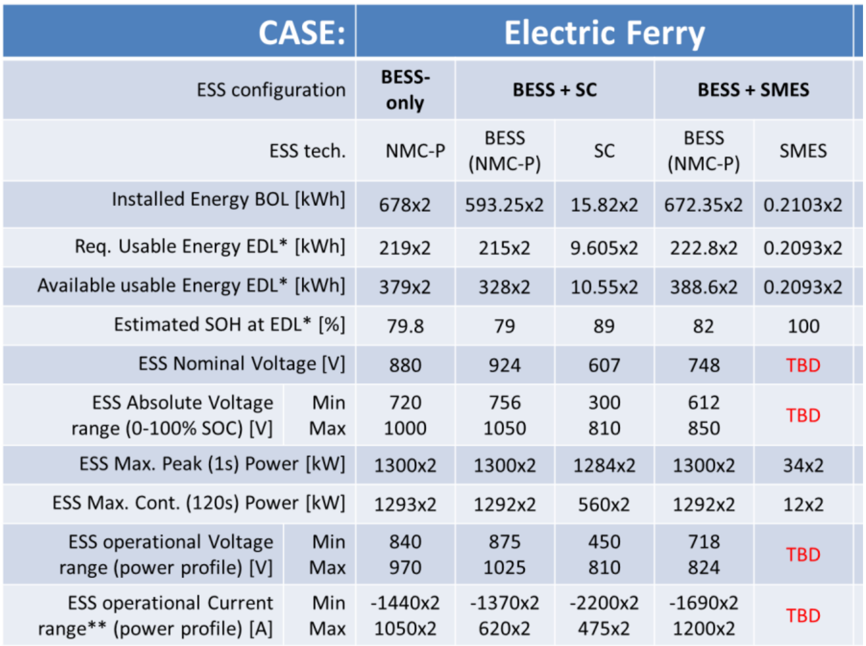
Seamless monitoring through CAN bus Phoenix connector, DC line control with the use of a manual handle for the main switch, and maximum safety while ensuring optimal cooling through the IP20 enclosure.

SkelGrid's innovative design unlocks new applications and possibilities.

Figure 5: The SkelGrid rack-system for supercapacitors from Skeleton

2.1.1 SC concept design case Electric Ferry

Results from the study on the Electric Ferry are collected in the following table:



CASE:		Electric Ferry				
ESS configuration		**BESS-only**	**BESS + SC**		**BESS + SMES**	
ESS tech.		NMC-P	BESS (NMC-P)	SC	BESS (NMC-P)	SMES
Installed Energy BOL [kWh]		678x2	593.25x2	15.82x2	672.35x2	0.2103x2
Req. Usable Energy EDL* [kWh]		219x2	215x2	9.605x2	222.8x2	0.2093x2
Available usable Energy EDL* [kWh]		379x2	328x2	10.55x2	388.6x2	0.2093x2
Estimated SOH at EDL* [%]		79.8	79	89	82	100
ESS Nominal Voltage [V]		880	924	607	748	TBD
ESS Absolute Voltage range (0-100% SOC) [V]	Min Max	720 1000	756 1050	300 810	612 850	TBD
ESS Max. Peak (1s) Power [kW]		1300x2	1300x2	1284x2	1300x2	34x2
ESS Max. Cont. (120s) Power [kW]		1293x2	1292x2	560x2	1292x2	12x2
ESS operational Voltage range (power profile) [V]	Min Max	840 970	875 1025	450 810	718 824	TBD
ESS operational Current range** (power profile) [A]	Min Max	-1440x2 1050x2	-1370x2 620x2	-2200x2 475x2	-1690x2 1200x2	TBD

Table 3: Power and energy distribution Electric Ferry case

From the table above the ESS with SC from Skeleton for the Electric Ferry case is dimensioned to cover 120 seconds power peaks of 560kW:

Total number of modules	70 (7 racks with 10 modules each)
ESS with SC	5 series 14 parallel SkelMod 162V 62F (5x14=70 modules)
Module voltage	162 VDC
ESS output voltage	810 VDC
Module max stored energy	229.5 Wh
Total ESS max stored energy	16 kWh

Table 4: Main parameters for SC in the Electric Ferry case

In this case 2 ESS's are needed.

2.1.2 SC concept design case OSV-AHC

Results from the study on the OSV+AHC are collected in the following table:

CASE:		**OSV + AHC**				
ESS configuration		**BESS-only**	**BESS + SC**		**BESS + SMES**	
ESS tech.		LFP	BESS (LFP)	SC	BESS (LFP)	SMES
Installed Energy BOL [kWh]		1209	1092	1.950	1123.2	0.133
Req. Usable Energy EDL* [kWh]		578.50	578.50	1.343	578.5	0.13038
Available usable Energy EDL* [kWh]		864	771	1.359	796	0.13038
Estimated SOH at EDL* [%]		89	88	92.9	88.5	100
ESS Nominal Voltage [V]		693	693	607	739.2	TBD
ESS Absolute Voltage range (0-100% SOC) [V]	Min Max	567 798	567 798	300 810	604.8 851.2	TBD
ESS Max. Peak (1s) Power [kW]		4300	4000	850	4110	185
ESS Max. Cont. (120s) Power [kW]		3400	3400	140	3400	30
ESS operational Voltage range (power profile) [V]	Min Max	630 720	620 725	410 810	670 770	TBD
ESS operational Current range** (power profile) [A]	Min Max	-1700 6700	-1700 6325	-1110 1110	-1580 6050	TBD

Table 5: Power and energy distribution OSV-AHC case

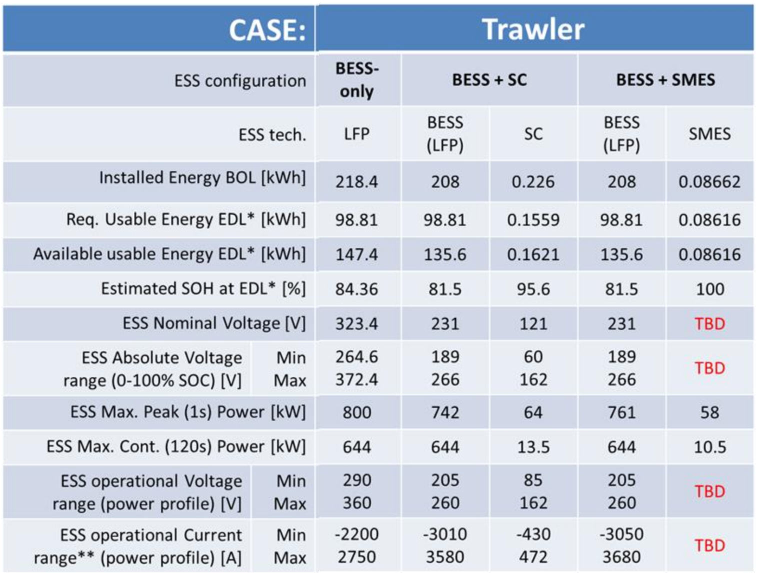
From the table above the ESS with SC from Skeleton for the OSV-AHC case is dimensioned to cover 120 seconds power peaks of 140kW:

Total number of modules	10 (1 rack with 10 modules)
ESS with SC	5 series 2 parallel SkelMod 162V 62F (5x2=10 modules)
Module voltage	162 VDC
ESS output voltage	810 VDC
Module max stored energy	229.5 Wh
Total ESS max stored energy	2295 Wh

Table 6: Main parameters for SC in the OSV-AHC case

2.1.3 SC concept design case Trawler

Results from the study on the Trawler case are collected in the following table:



CASE:		Trawler				
ESS configuration		BESS-only	BESS + SC		BESS + SMES	
ESS tech.		LFP	BESS (LFP)	SC	BESS (LFP)	SMES
Installed Energy BOL [kWh]		218.4	208	0.226	208	0.08662
Req. Usable Energy EDL* [kWh]		98.81	98.81	0.1559	98.81	0.08616
Available usable Energy EDL* [kWh]		147.4	135.6	0.1621	135.6	0.08616
Estimated SOH at EDL* [%]		84.36	81.5	95.6	81.5	100
ESS Nominal Voltage [V]		323.4	231	121	231	TBD
ESS Absolute Voltage range (0-100% SOC) [V]	Min	264.6	189	60	189	TBD
	Max	372.4	266	162	266	
ESS Max. Peak (1s) Power [kW]		800	742	64	761	58
ESS Max. Cont. (120s) Power [kW]		644	644	13.5	644	10.5
ESS operational Voltage range (power profile) [V]	Min	290	205	85	205	TBD
	Max	360	260	162	260	
ESS operational Current range** (power profile) [A]	Min	-2200	-3010	-430	-3050	TBD
	Max	2750	3580	472	3680	

Table 7: Power and energy distribution Trawler case

From the table above the ESS with SC from Skeleton for the Trawler case is dimensioned to cover 120 seconds power peaks of 13.5kW:

Total number of modules	1 (1 rack with 1 module)
ESS with SC	1 SkelMod 162V 62F
Module voltage	162 VDC
ESS output voltage	162 VDC
Module max stored energy	229.5 Wh
Total ESS max stored energy	229.5 Wh

Table 8: Main parameters for SC in the Trawler case

2.2 Mechanical integration of SC

2.2.1 SC location case Electric Ferry

<u>Location:</u>

The locations of the 7 SC racks for the Electric Ferry are in a separate room next to the BESS and Engine rooms at the forward and aft locations as shown in the figure below.

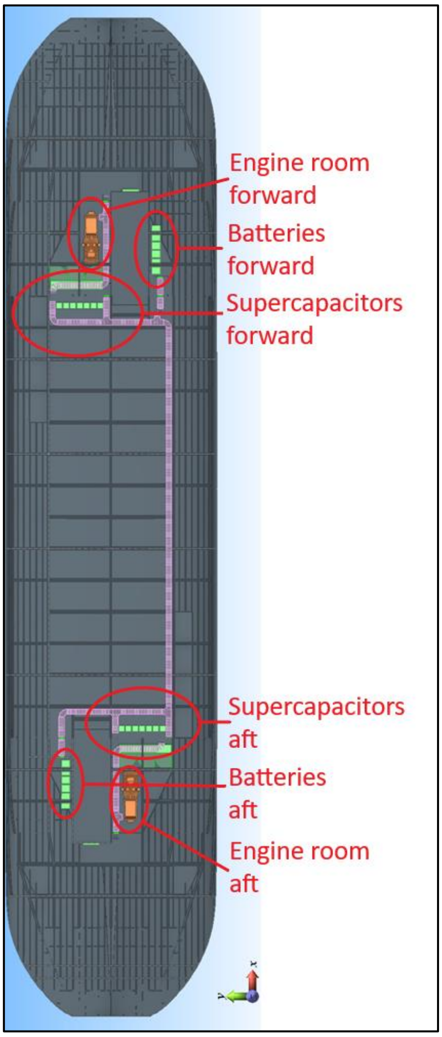


Figure 6: Positions of the forward and aft SC rooms in case Electric Ferry

Dimensions:

	Dimensions (mm)
Rack height	2350
Rack footprint	600 x 600 = 0.36 m^2
Total footprint ESS with SC	0.36 m^2 x 7 = 2.52 m^2

Weight:

	Weight
Rack weight	600 kg
Total weight ESS with SC	4.200 kg

2.2.2 SC location case OSV-AHC

<u>Location:</u>

Because the ESS containing SC in the OSV-AHC case only uses 1 rack this installation can be placed in the existing Energy Storage Room on the Tank Top deck on the vessel.

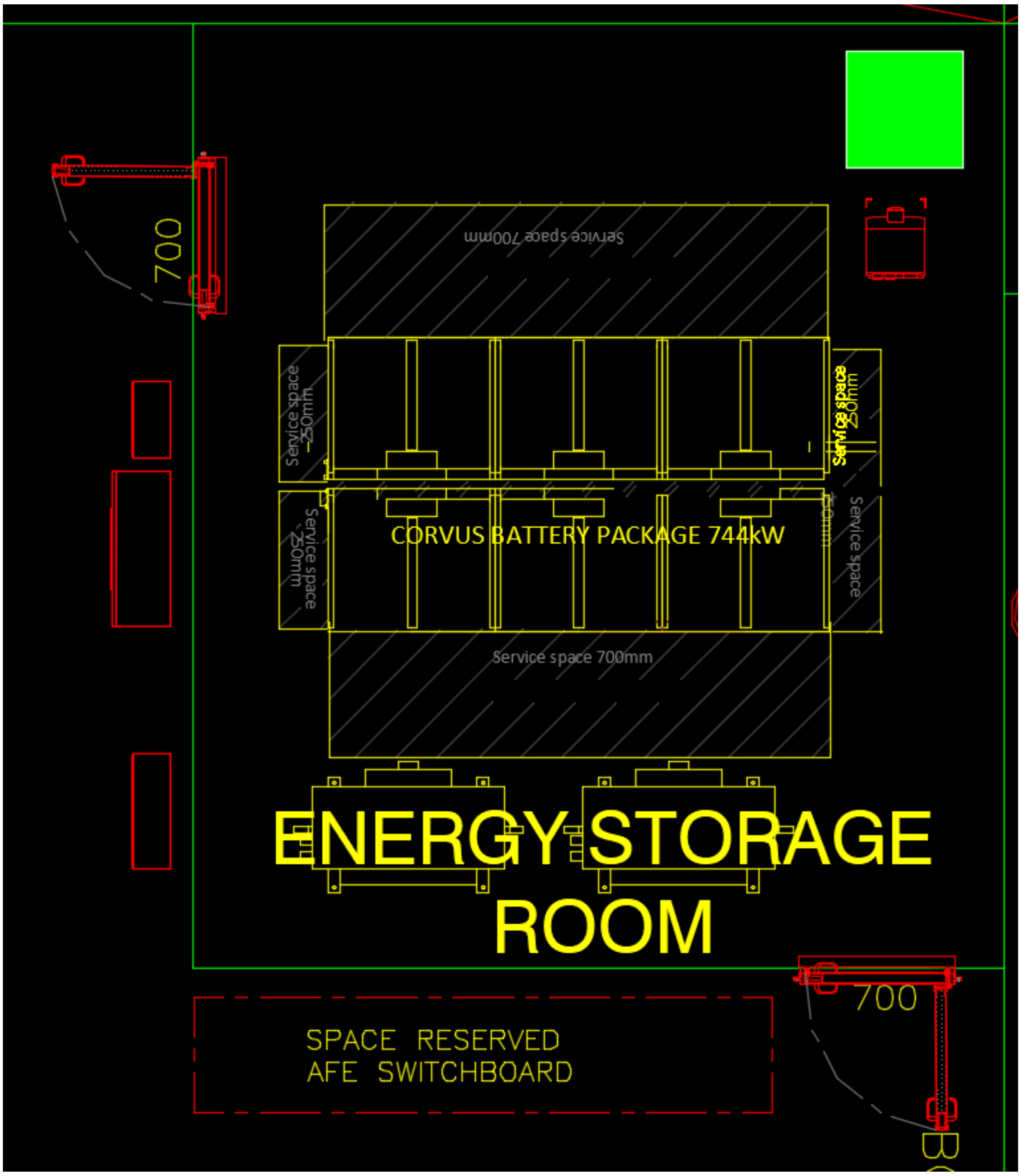


Figure 7: Illustration of SC (green) placed in the ESS room in case OSV-AHC

Dimensions:

	Dimensions (mm)
Rack height	2350
Rack footprint	600 x 600 = 0.36 m^2
Total footprint ESS with SC	0.36 m^2 x 1 = 0.36 m^2

Weight:

	Weight
Rack weight	600 kg
Total weight ESS with SC	600 kg

2.2.3 SC location case Trawler

Location:

Because the ESS containing SC in the Trawler case only uses 1 rack this installation can be placed in the existing Energy Storage Room on the vessel.

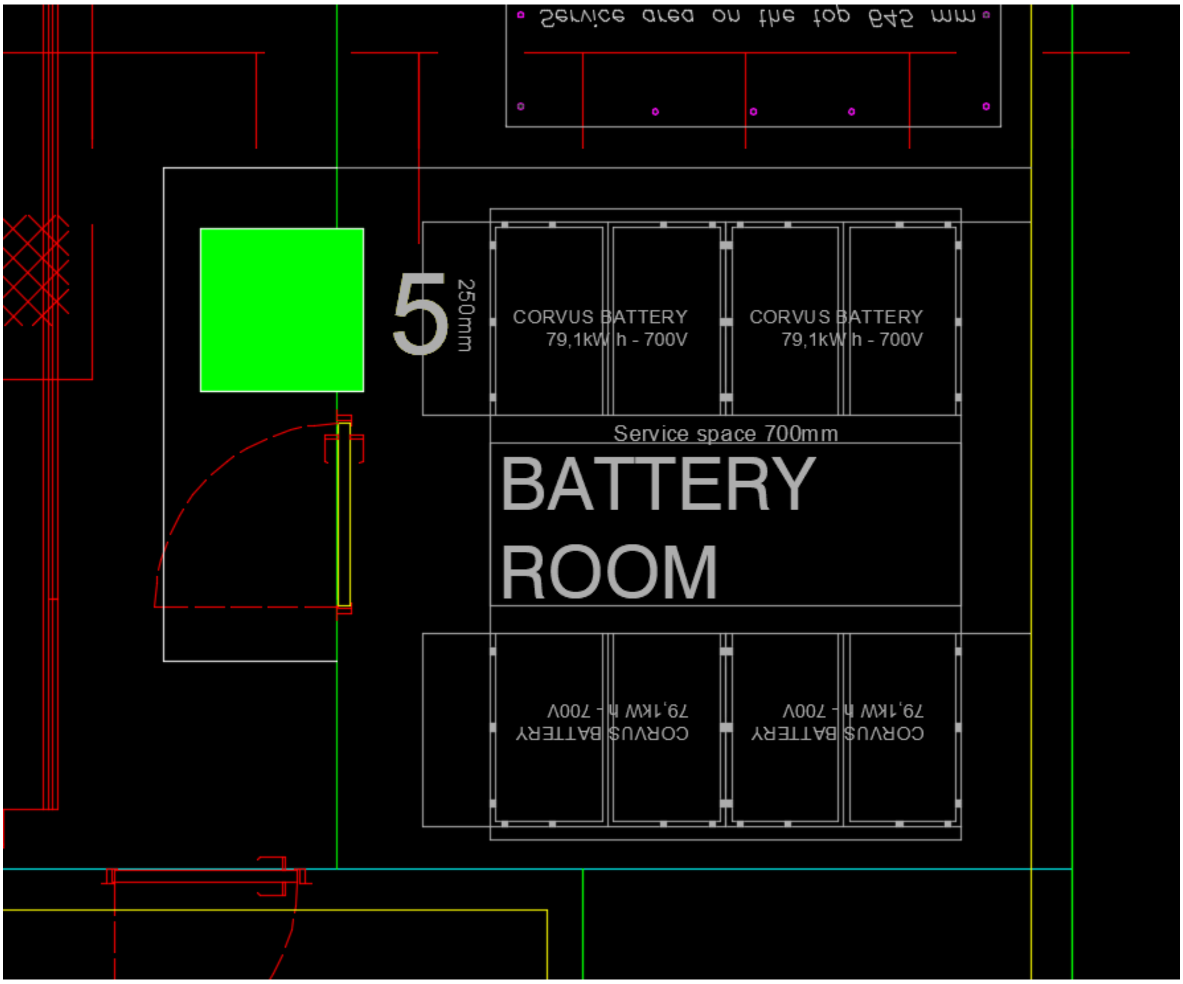


Figure 8: Illustration of SC (green) placed in extension of ESS room

Dimensions:

	Dimensions (mm)
Rack height	2350
Rack footprint	600 x 600 = 0.36 m^2
Total footprint ESS with SC	0.36 m^2 x 1 = 0.36 m^2

Weight:

	Weight
Rack weight	285 kg
Total weight ESS with SC	285 kg

2.2.4 Installing the SC components - all cases

Connecting Power Cables:

All modules are shipped with a shorting circuit. Ensure the DC power cables remain shorted during installation!

STEP	ACTION
1	Remove the cabinet roof
2	Disconnect wires connected to the cooling fan
3	Remove IP cover from switchgear module and disconnect DC power cables that connect the switchgear to the supercapacitor modules
4	Disconnect all of the auxiliary wiring, connecting switchgear module to the master controller
5	5. Remove switchgear module from the enclosure.
6	The busbars should be visible on the left side wall, connect the incoming power cables using cable lugs, observe correct polarity.
7	Connect PE grounding wore to the grounding wire at the bottom of the cabinet.
8	Replace the switchgear unit in the enclosure.
9	Reconnect the auxiliary wiring to the switchgear module

10	Reconnect DC power cables to the modules (make sure the DC power cables remain shorted until all works on the cabinet are completed).
11	Connect auxiliary 230 V to the front of switchgear module.
12	Connect communication line to the customer system.
13	Reconnect the cooling fan wires to the fan
14	Reassemble the roof.

Table 9: Steps to perform SC power cables connections

SWG01 Mechanical switchgear installation:

STEP	**DESCRIPTION**
1	Ensure Proper Rack Compatibility: The Switchgear unit is designed to fit a standard 19” rack enclosure. Make sure the rack cabinet and its features are compatible with EN 60297-3-100 standard.
2	Safety Precautions: To prevent potential danger, it is essential to have two people for safely mounting the Switchgear unit into the rack cabinet. This ensures stability and prevents accidents during installation. Pay attention that the Switchgear is installed at the very top shelf of the cabinet. At the height of 1960 mm it is recommended to use additional mounting equipment that will prevent integrators from manipulating the Switchgear at such heights.
3	Positioning the Switchgear: Place the Switchgear on the horizontal mounting rails of the rack cabinet. Ensure that the module is aligned properly and entered on the rails.
4	Securing the Switchgear: Use four M6 bolts along with corresponding washers to secure the face of the Switchgear onto the vertical railings of the rack cabinet. Position the bolts through the mounting holes on the face of the module and insert them into the vertical railings. Tighten the bolts securely to ensure the module is firmly attached to the rack cabinet.
5	Double-Check Installation: After securing the Switchgear, double-check all bolts and connections to ensure they are tightened properly. Verify that the Switchgear is securely mounted and there are no loose components.
6	Testing: Before proceeding with any further installation or operation, conduct a brief test to ensure the Switchgear is functioning correctly and securely installed in the rack cabinet.

7	Maintenance: Regularly inspect the mounting hardware and connections to ensure they remain secure over time. If any issues or concerns arise, promptly address them to Skeleton Technologies to maintain the safety and integrity of the installation.

Table 10: Steps to perform SC SWG01 Mechanical switchgear installation

SWG01 High-power connection:

STEP	**DESCRIPTION**
1	Terminal Location and Configuration: The Switchgear has two pairs of power connectors. One is located at the front panel of the Switchgear which enables connection between the switchgear and modules. The second pair of connectors is located at the back of the switchgear and is meant for connecting the Switchgear to the SkelGrid system and eventually to the integrator. 1. Front panel high power terminals: situated on the front panel of the switchgear, equipped with one fastening hole designed for M10 fastener. Each terminal shall be fastened with 25 Nm torque. 2. Back high-power terminals: copper busbars not requiring any fasteners, the switchgear is simply slid into quick- connectors with which SkelGrid system is equipped.
2	For each terminal a high-power cable with lugs, M10 fastener, plane- and lock-washer is required, ensuring correct electrical connections between the units for both series and parallel configurations.

Table 11: Steps to perform SWG01 High-power connection

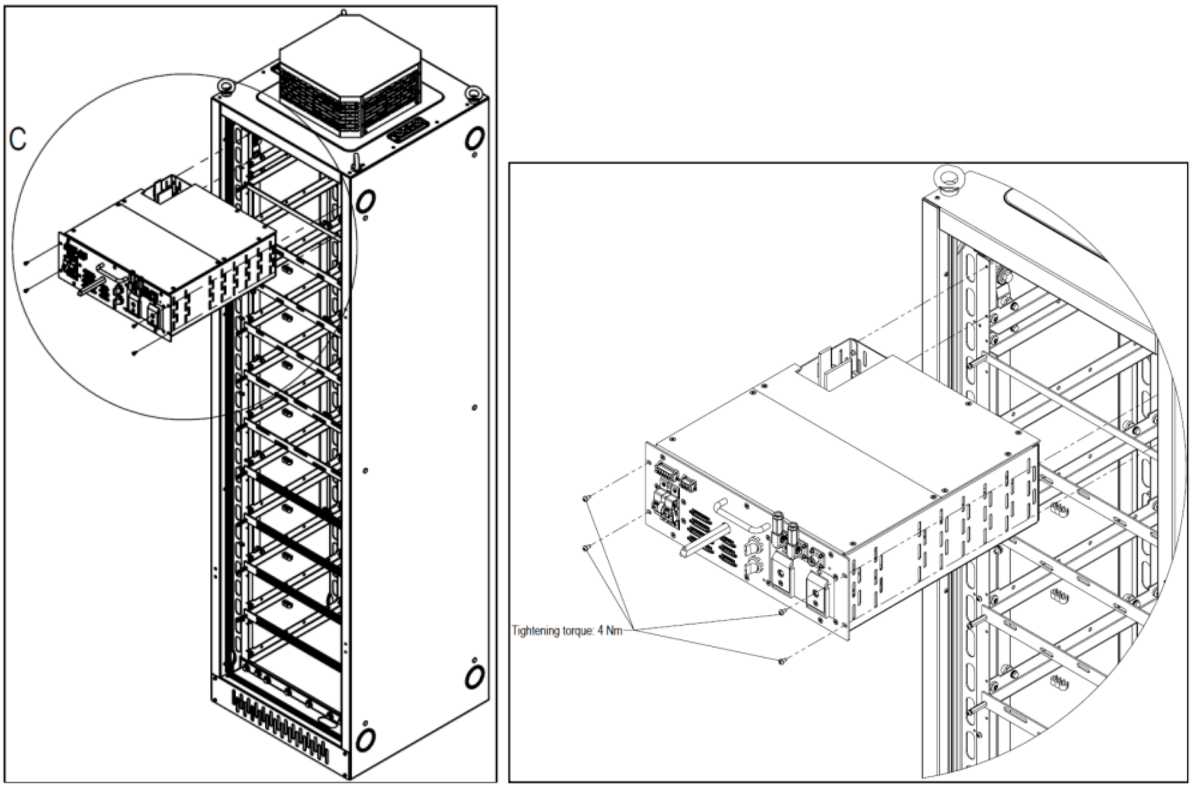


Figure 9: Switchgear mechanical installation

MD01 Module Mechanical installation:

STEP	DESCRIPTION
1	Protective Barrier: The power terminals of the SMA162V62F module need to be behind a protective barrier to comply with safety standards. This barrier must at least meet the requirement of protective type IPXXB, and it should only be removable using a tool or key, or after de-energization of the modules. The barrier must also display the warning symbol and indicate the minimum discharge time required for discharging the capacitors under the worst-case conditions.
2	Protective Shrouds: The hazardous live parts of the SMA162V62F module should be covered by protective shrouds. These shrouds are part of the SkelGrid 2.0 Energy Storage System 19-inch rack assembly. SkelGrid 2.0 has a total of 5 shrouds for module protection, 4 of which have a product number S50021.P01 and the very top one has a product number S50026.P01. The protective shroud should be fastened to the vertical rails of the 19-inch rack frame with a maximum torque of 2 Nm.

BEFORE UNPACKING THE SMA162V62F MODULES, IT IS CRUCIAL TO INSPECT THE SHIPPED PACKAGES FOR ANY SIGNS OF DAMAGE. FOLLOW THESE STEPS TO ENSURE SAFE HANDLING AND INSTALLATION:	
3	Inspect Shipped Packages: Before opening the packages, carefully examine them for any visible signs of damage such as tears, dents, or punctures. If any damage is noticed, it is important to report it immediately to the carrier or delivery service. Document the damage with photographs if possible.
4	Lifting Precautions: The SMA162V62F modules are equipped with extra protection for safe transport. However, it is still essential to handle them with care. The modules weigh approximately 35 kg, necessitating proper lifting techniques. For safety reasons, it is strongly advised to lift the module with the assistance of at least two people.
5	Using Handles: Lift the module using the designated handles of the module. These handles are designed to facilitate safe lifting and handling. Avoid lifting the module by any other means or attempting to carry it without utilizing the handles.
6	Team Lifting: When lifting the module, coordinate with your lifting partner(s) to ensure synchronized movement and balanced weight distribution. Communicate clearly and establish a plan before lifting to prevent accidents or strain injuries.
7	Placement Options: The SMA162V62F module can be positioned both horizontally and vertically, depending on the installation requirements and available space. Note that while the module can be placed horizontally or vertically for storage or temporary positioning, it should only be installed according to the manufacturer's installation guidelines.
8	Stable Surface: Place the module on a stable and level surface once it has been safely lifted and transported to its intended location. Avoid placing the module on uneven or unstable surfaces to prevent tipping or shifting during installation.

Table 12: Steps to perform MD01 Module Mechanical installation

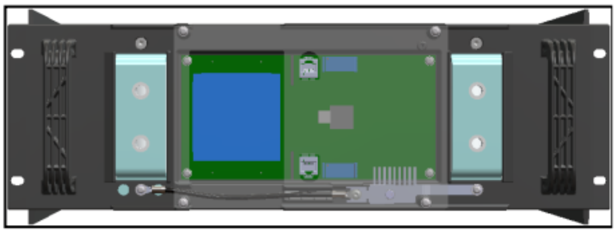


Figure 10: SkelGrid Module Mechanical Installation

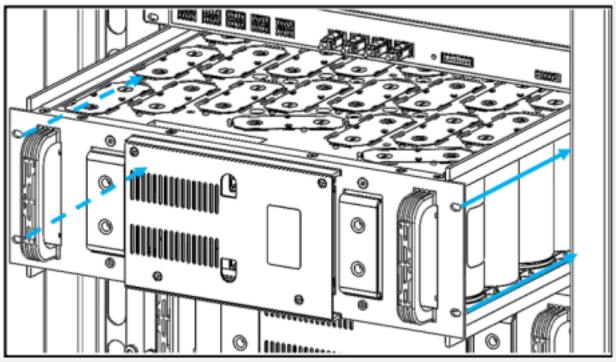
	MOUNTING: **THE SMA162V62F IS DESIGNED FOR A STANDARD 19” RACK ENCLOSURE.** **EACH MODULE WEIGHS 33 KG AND SHOULD BE HANDLED BY TWO PERSONS.**
	 Four (4) M6 bolts with corresponding washers must be used to secure the face of the SMA162V62F onto the vertical railings of the rack cabinet. The support railings must be able to carry the weight of the SMA162V62F.

Table 13: Step to perform SkelGrid Module Mechanical Installation

High-power connection:

1	Terminal Location and Configuration: The high-power terminals are situated on the front panel of the module. Each terminal is equipped with two fastening holes designed for M10 fasteners. Having two fastening holes enables both series and parallel connections of module-to-module busbars.
2	Busbar Connection Kit: To interconnect modules, a busbar kit (product number S30035.A01) is required. This kit likely includes the necessary components for safely and securely connecting the modules together using busbars. It ensures proper electrical connections between the modules for series and parallel configurations.

Table 14: Steps to perform SC High-power connection

MD01 Electrical Installation:

Electrical connections are all located on the front panel of module.

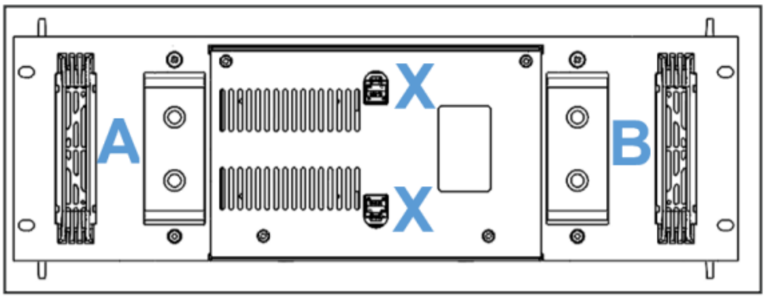


Figure 11: SkelGrid module electrical connection (front view)

High power terminals are located on the front panel of the module. Terminals are equipped with M10 threaded connections

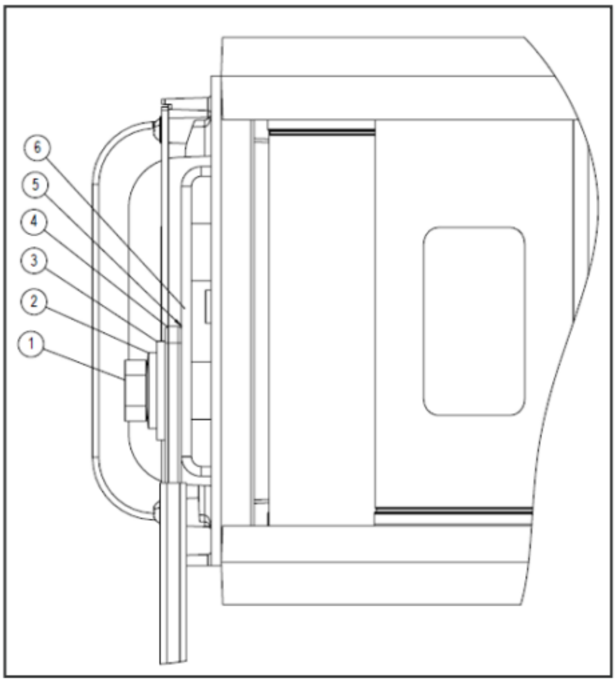


Figure 12: MD01 Item Description:

1. *M10 x 25 bolts (e.g. DIN 933)*
2. *M10 Belleville washer (e.g. D6796)*
3. *M10 large washer (e.g. DIN 9021),*
4. *Copper / aluminium busbar*
5. *M10 bimetallic washer (bimetallic washer not needed if aluminium busbar is used)*
   SMA162V62F module aluminium terminal

Auxiliary cables containing communication and 24V DC supply are connected to standard ethernet aux connection port in front of the module. Cable is connected from one module to another and back to the master controller from last module in string.

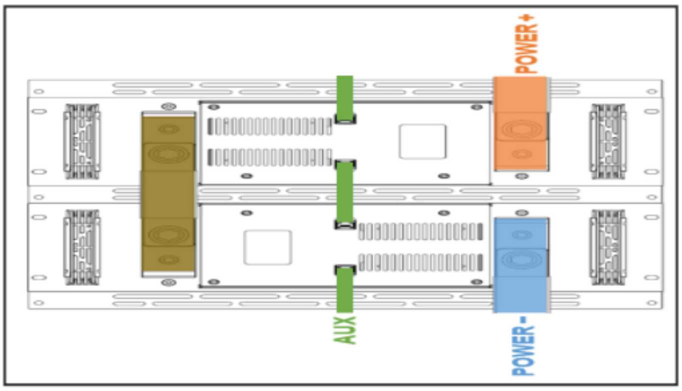


Figure 13: SkelGrid MD01 electrical connections (front view)

2.2.5 Ventilation SC - all cases

One supercapacitor cabinet´s cooling system is based on roof-mounted centrifugal fan so that cool air is taken in through the front of the cabinet and exhausted from the top of the cabinet. Speed of the fan is controlled by the master controller unit and speed is adjustable from 0% to 100%, so that maximum consumption is 312W at maximum speed and airflow of 1,850 m^3/h.

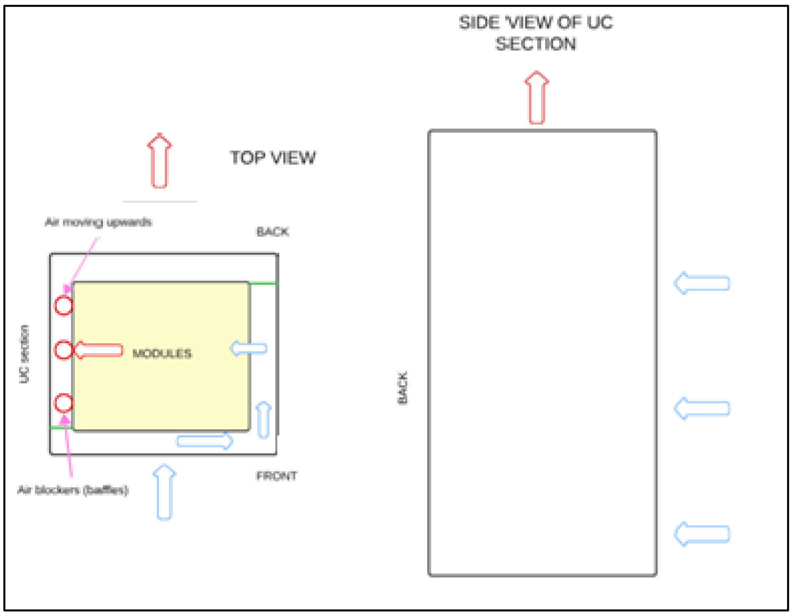
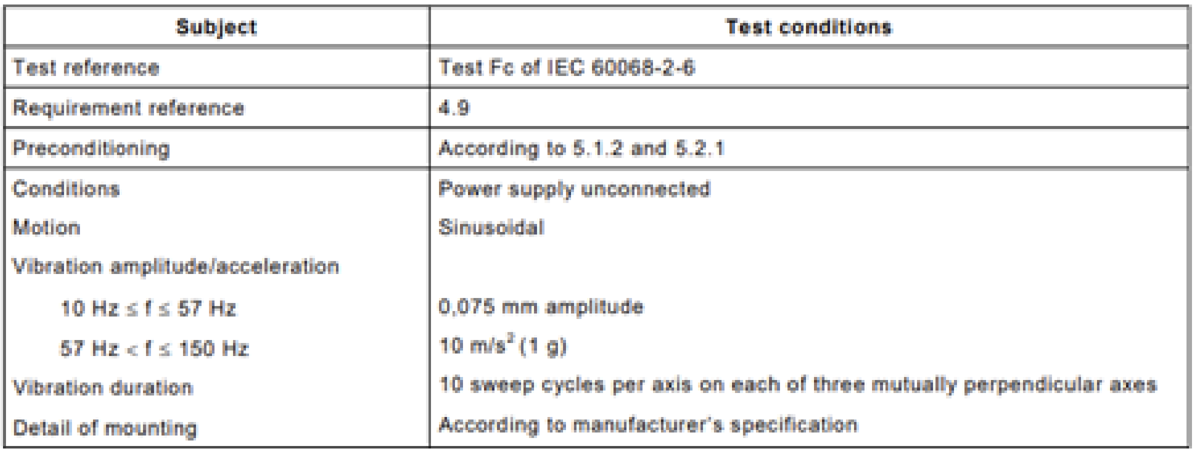


Figure 14: SC cabinet´s cooling system

According to risk assessment carried out in this project it is recommended to consider installing two (2) fans for the ventilation of this compartment for redundancy. The loss of ventilation may cause overheating and potential system failure.

2.2.6 Vibration SC - all cases

Skelmod 162V62F module is compliant with vibration acc IEC60068-2-6: 2007 standard, which defines the vibration test applicable for equipment which during transportation or service may be subjected to conditions involving vibration of a harmonic pattern generated by rotating, pulsating or oscillating forces, such as occur in ships, aircraft, land vehicles, rotorcraft and space applications or are caused by machinery and seismic phenomena.



Subject	Test conditions
Test reference	Test Fc of IEC 60068-2-6
Requirement reference	4.9
Preconditioning	According to 5.1.2 and 5.2.1
Conditions	Power supply unconnected
Motion	Sinusoidal
Vibration amplitude/acceleration	
10 Hz ≤ f ≤ 57 Hz	0,075 mm amplitude
57 Hz < f ≤ 150 Hz	10 m/s^2 (1 g)
Vibration duration	10 sweep cycles per axis on each of three mutually perpendicular axes
Detail of mounting	According to manufacturer's specification

Table 15: Sinusoidal vibration test compliance of supercapacitor module

2.2.7 EMC SC - all cases

Supercapacitor system is modular, and the main building block is the 162V 62 Farad module, on which the compliance of EMC according to IEC 61000-6-8: 2020 and IEC 6100-6-2: 2019 is done. Standards describe EMC immunity requirements, which apply to electrical and electronic apparatus intended for use in industrial, light-industrial and commercial environments.

There should be an evaluation done if this also applies in marine and what kind of differences there could be.

2.3 Electrical integration of SC

The electrical integration of SC is done by placing a DC-DC converter (see chapter 2.3.4 Description of integrating components for SC – all cases) between each of the ESS's with SC and the DC switchboard in all the 3 vessel cases investigated.

The ESS with SC is exchanging energy with the power plant through the DC-DC converters based on the control strategies described in chapter 4.1 for all 3 cases.

2.3.1 Electrical integration SC case Electric Ferry

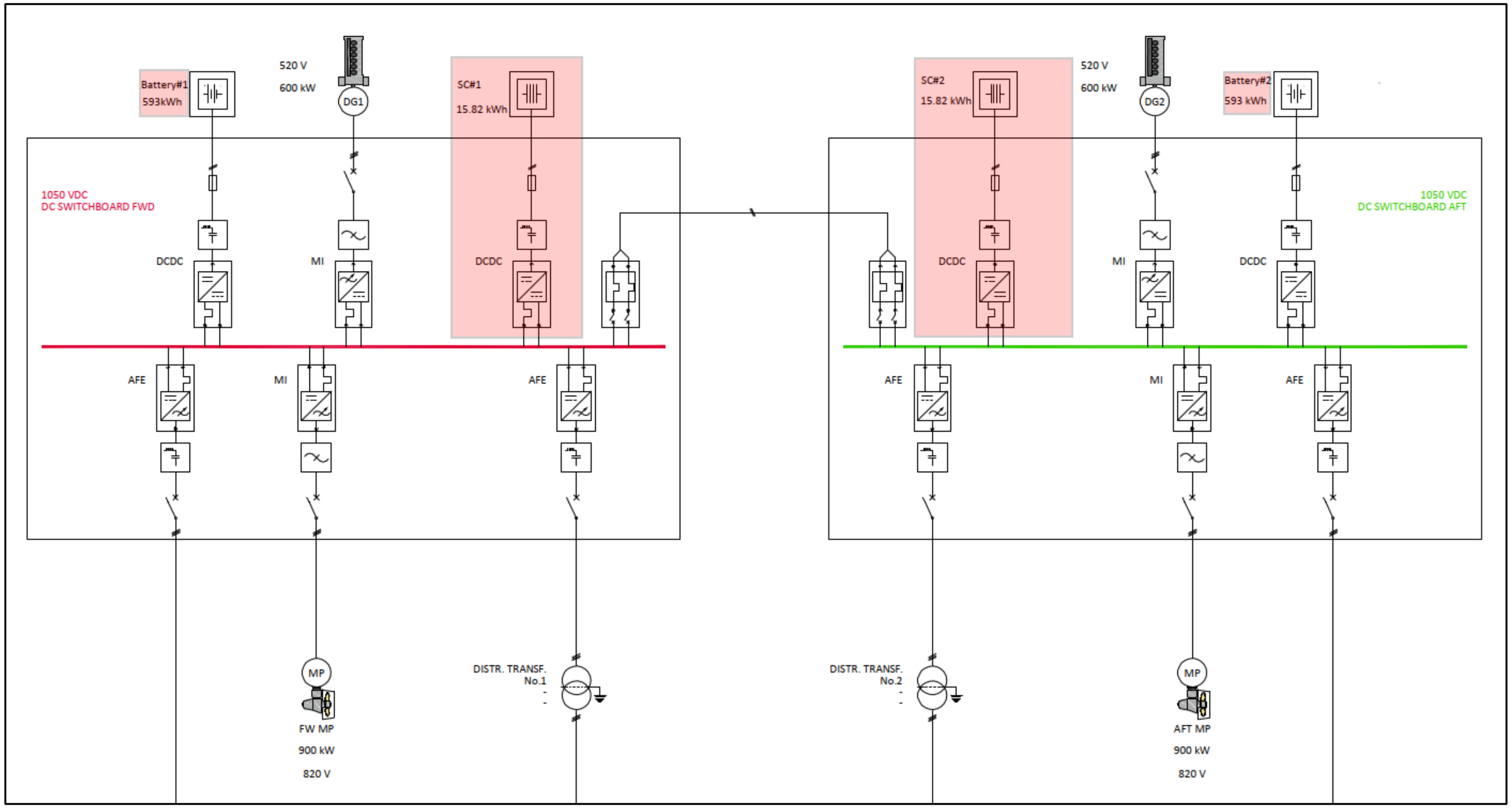


Figure 15: Single-Line-Diagram for case Electric Ferry with battery and SC

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2.3.2 Electrical integration SC case OSV-AHC

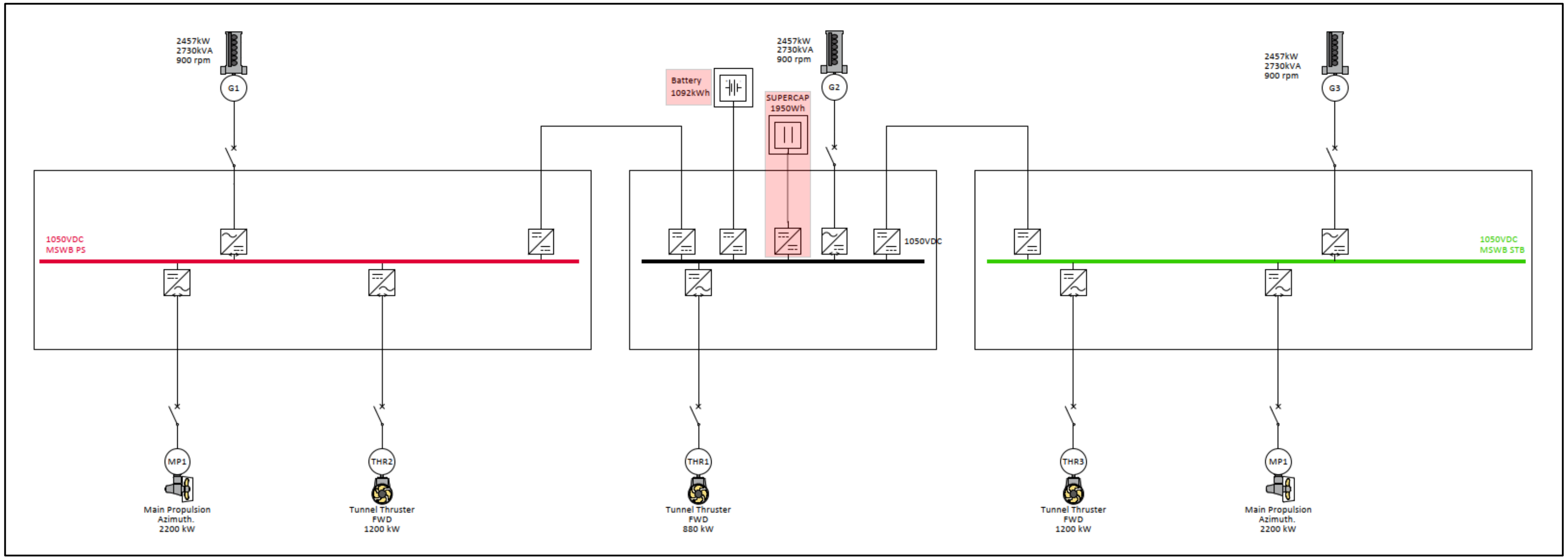

Figure 16: Single-Line-Diagram for case OSV-AHC with battery and SC

2.3.3 Electrical integration SC case Trawler

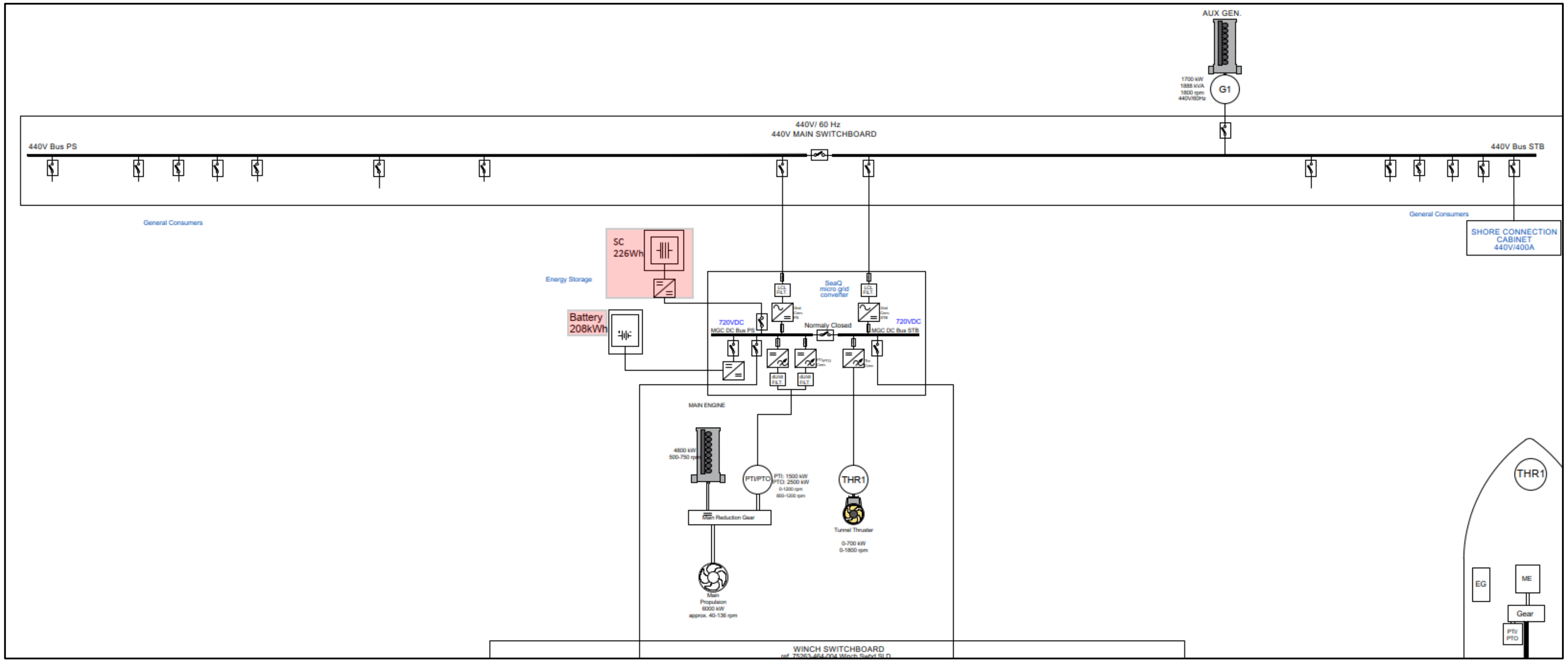

Figure 17: Single-Line-Diagram for case Trawler with battery and SC

2.3.4 Description of integrating components for SC – all cases

The DC-DC converters that integrate the new ESS with SC into the vessels energy system in the figures above are based on a non-isolated half-bridge topology with interleaving (two insulated gate bipolar transistors (IGBTs)). The number of interleaved bridges depends on each half-bridge current rating versus the actual current rating required (typically 2-4 bridges interleaved). The two IGBTs are controlled based on the complementary control scheme, which greatly simplifies the control of power flow. In this way, the control input does not need to switch between buck- or boost mode as the power reference changes from charging to discharging, respectively. The converter topology, combined with the control approach, is formally referred to as either a *synchronous boost converter*, or "*synchronous buck converter*, depending on the predefined power flow direction. Alternatively, it is also commonly referred to as a bidirectional DC-DC converter. During interleaving, it is crucial to coordinate the pulse-width modulation (PWM) signals to reduce the low-voltage side current ripple. For instance, in a two-bridge topology this is achieved by delaying the gate signal of the second bridge by half the switching period ($T_{sw}/2$), or 180 degrees. This significantly reduces the equivalent ripple compared to a single converter. This also reduces the need for filtering on both the low- and high-voltage side. The PWM signals are typically generated based on the output of the inductor dc current controllers (dcc), which constitutes the *inner* control loop. To generate a current reference, two options are generally adopted: 1) a power reference is recalculated into a current reference, or 2) the current reference is generated by an *outer* loop dc voltage controller (DVC). If the DC-DC converter is part of a larger power system, the DVC can be modified by including droop control as well. This enables load sharing when parallelled with multiple source converters in a power system.

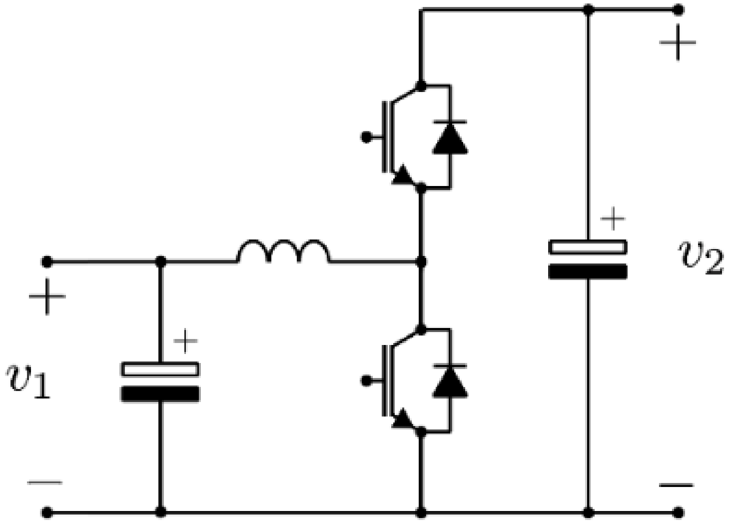

Figure 18: Bidirectional DC-DC converter

2.4 Safety for SC

Recommendations from D5.3 Risk assessment analysis of ESS:

- No interconnection of the ventilation ducts between the compartment containing the SC and the rest of the vessel.
- To have an emergency shutdown for this ventilation from a remote location.
- Manual activation capability of fi-fi system from a remote location.
- External fire-fighting system with cooling capacity, such as water mist or sprinkler system.

3 Integrating Superconducting Magnetic Energy Storage (SMES)

The standardization of integration of SMES onboard vessels assumes the solution is type approved for marine usage. The rules compliance matrix for SMES below shows that the SMES from ASG does not comply with any of the applicable standards needed for approval at the time when this report was prepared. The SMES from ASG used in this project was at TRL 3 at the beginning of the project.

Standards/Rules for SMES	Applicable	Compliant	To be compliant	Comment
a. IEC 62391-1 Fixed electric double-layer capacitors for use in electric and electronic equipment – Part 1: Generic specification	N			
b. IEC 62391-2 Fixed electric double-layer capacitors for use in electronic equipment – Part 2: Sectional specification – Electric double layer capacitors for power application	N			
c. IEC 62391-2-1 Fixed electric double-layer capacitors for use in electronic equipment – Part 2-1: Blank detail specification – Electric double-layer capacitors for power application – Assessment level EZ	N			
d. IEC 62576 Electric double-layer capacitors for use in hybrid electric vehicles – Test methods for electrical characteristics	N			
e. IEC 60812 Analysis techniques for system reliability - Procedure for failure mode and effects analysis (FMEA)	Y	N	Y	
f. UL 810A: Standard for Electrochemical Capacitors	N			
g. NFPA 70: National Electrical Code 2017: Article 706 Energy Storage Systems	Y	N	Y	

h. IEC 60068-2-27:2008 Environmental testing - Part 2-27: Tests - Test Ea and guidance: Shock	Y	N	Y	
i. ISO 16750-3:2023 Road vehicles — Environmental conditions and testing for electrical and electronic equipment — Part 3: Mechanical loads	Y	N	Y	
j. IEC 62933 Series - Electrical energy storage (EES) systems	Y	N	Y	
k. IEC 60533:2015 Electrical and electronic installations in ships - Electromagnetic compatibility (EMC) - Ships with a metallic hull	Y	N	Y	
l. EN55011 Industrial, scientific and medical equipment. Radio-frequency disturbance characteristics. Limits and methods of measurement	Y	N	Y	
m. IEEE Guide for Design, Operation, and Maintenance of Battery Energy Storage Systems, both Stationary and Mobile, and Applications Integrated with Electric Power Systems	N			
n. ABS Requirements for Use of Supercapacitors in the Marine and Offshore Industries	N			

Table 16: Rules compliance matrix for SMES

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V-ACCESS; Grant agreement ID: 101096831

3.1 General description of SMES

The SMES is a device that can store energy in the magnetic field, so it is essentially a magnet. Since the energy is proportional to the inductance and the square of the current, a SuperConducting magnet is an interesting solution because it can carry a high current in a relatively compact space and therefore can store a lot of energy.

The SMES system is composed by 3 main parts:

1. SuperConducting magnet in its cryostat.
2. Cryogenic cooling system.
3. Power Conditioning System (PCS).

A typical schematic drawing of the SMES system showing the arrangement of the various components is shown in Figure 1. This sketch shows a cold source obtained with a cold head. An alternative solution for the future can be envisaged, such as the circulation of liquid hydrogen (LH2), when available on board, through a heat exchanger that replaces the cold head.

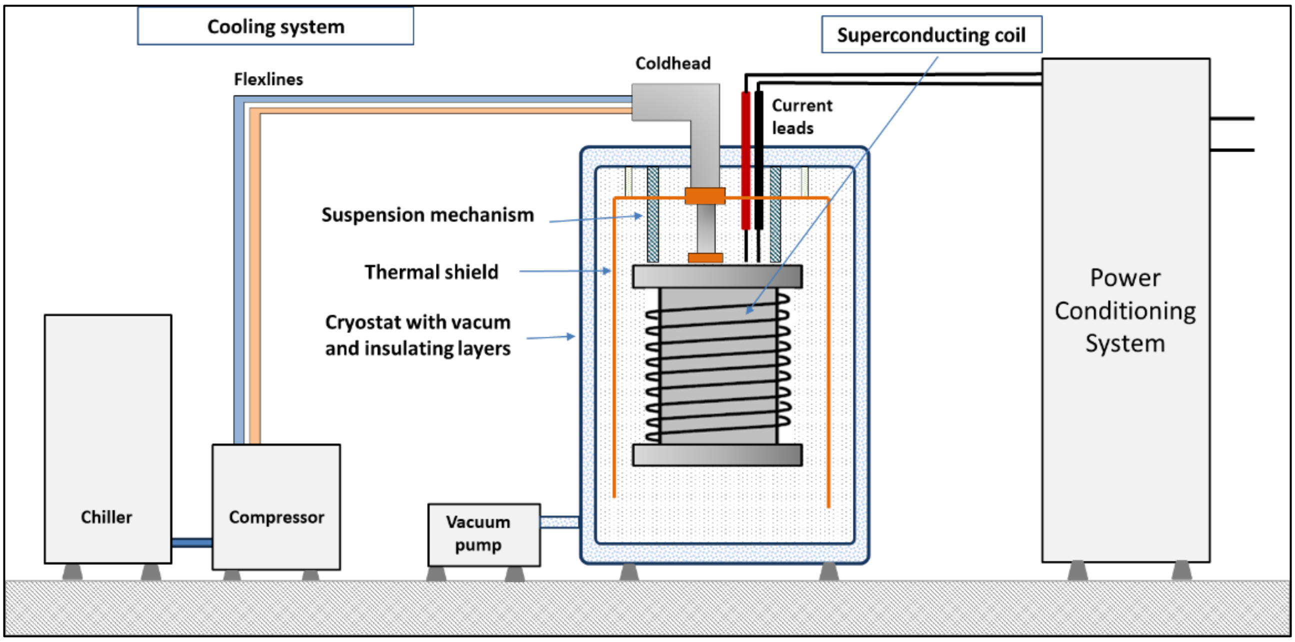


Figure 19: SMES conceptual scheme

NB: The chiller is used to cool down the compressor. A dedicated compressor is not necessary when such a system already exists on board

To give some more details of the connections of figure 1, the PID scheme of the SMES system is in Figure 20 below.

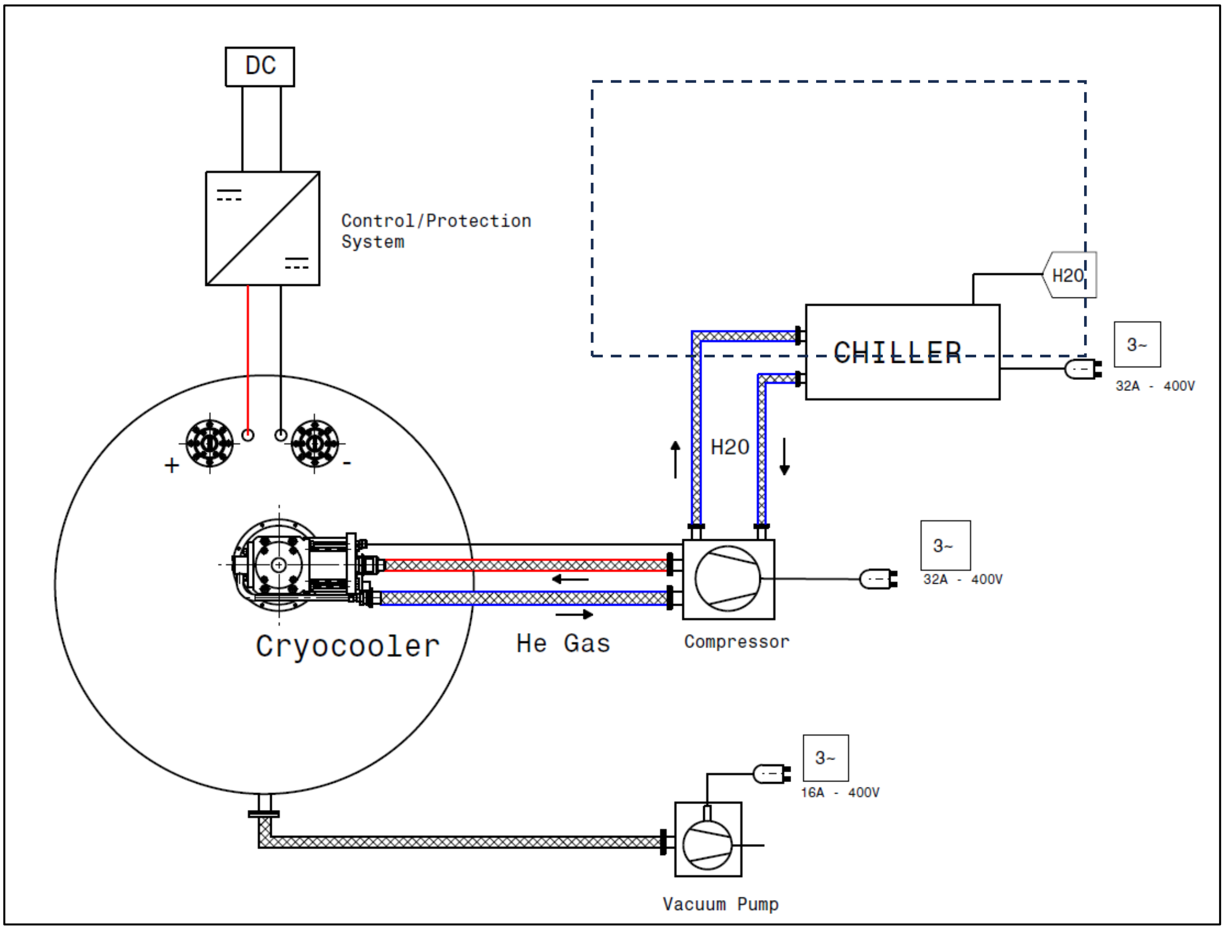


Figure 20: PID scheme of the SMES system

3.1.1 SMES concept design case Electric Ferry

Results from the study on the Electric Ferry are collected in Table 3: Power and energy distribution Electric Ferry case.

To meet the requirements in terms of **installed energy and power profile** defined for this use case, these are the main parameters of the SMES modules. The selected case is using 2 modules, each of them can store 750kJ (0.208kWh).

Voltage of DC bus, V	750
Max current, A	470
Inductance, H	6.80
Total Energy, kJ	750
Total Energy, kWh	0.208

Table 17: Main parameters for SMES Electric Ferry case

In the following pictures, a schematic drawing of the Superconducting coil and of the vacuum chamber, together with the picture of the real vacuum chamber containing the coil.

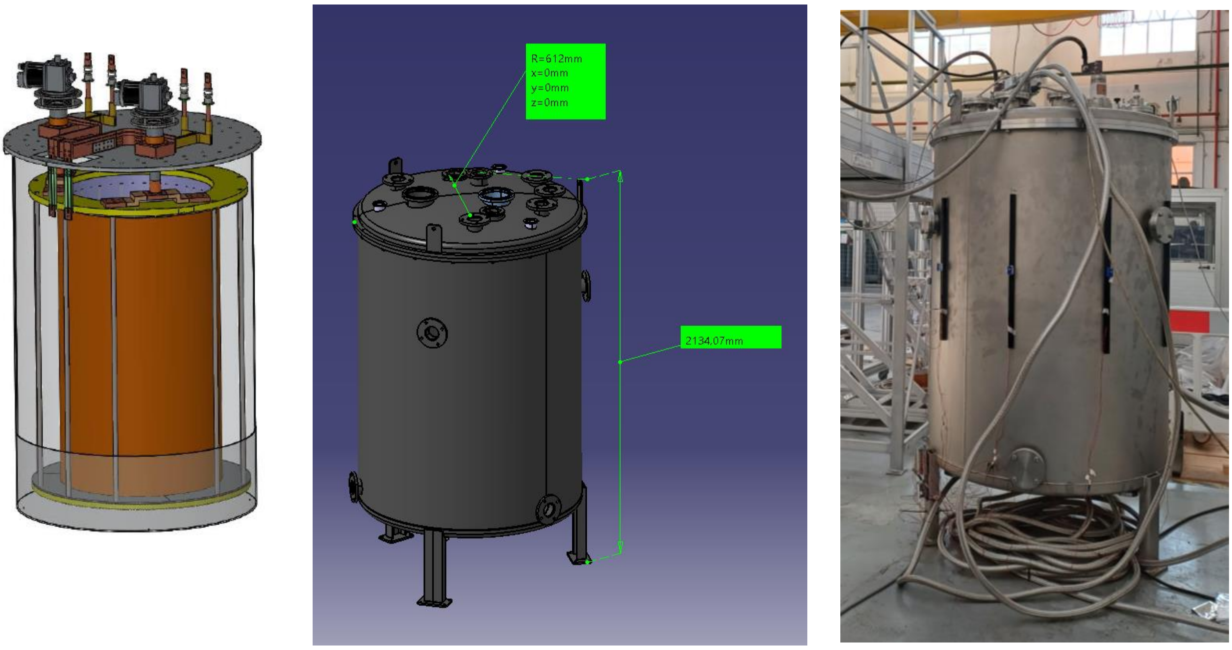


Figure 21: Schematic of the Superconducting coil (left), schematic of the vacuum chamber (middle) and picture of the real vacuum chamber containing the coil (right)

3.1.2 SMES concept design case OSV-AHC

Results from the study on the OSV+AHC are collected in Table 5: Power and energy distribution OSV-AHC case.

The size of the SMES is like in the electric ferry case. As the SMES is not used as a power source for travelling but for offshore servitude operations one module is needed. A lower operating current is needed (max current 400A). The main parameters of the OSVs' SMES are collected in the following table.

The installed energy and the SMES characteristics can meet the requirements also in terms of power profile. In the following graph, as an example, the SMES energy, power and currents, are plotted in a characteristics time frame obtained from the WP1 simulation of the spinning reserve case.

Voltage of DC bus, V	750
Max current, A	400
Inductance, H	6.80
Total Energy, kJ	540
Total Energy, kWh	0.15

Table 18: Main parameters for SMES OSV-AHC case.

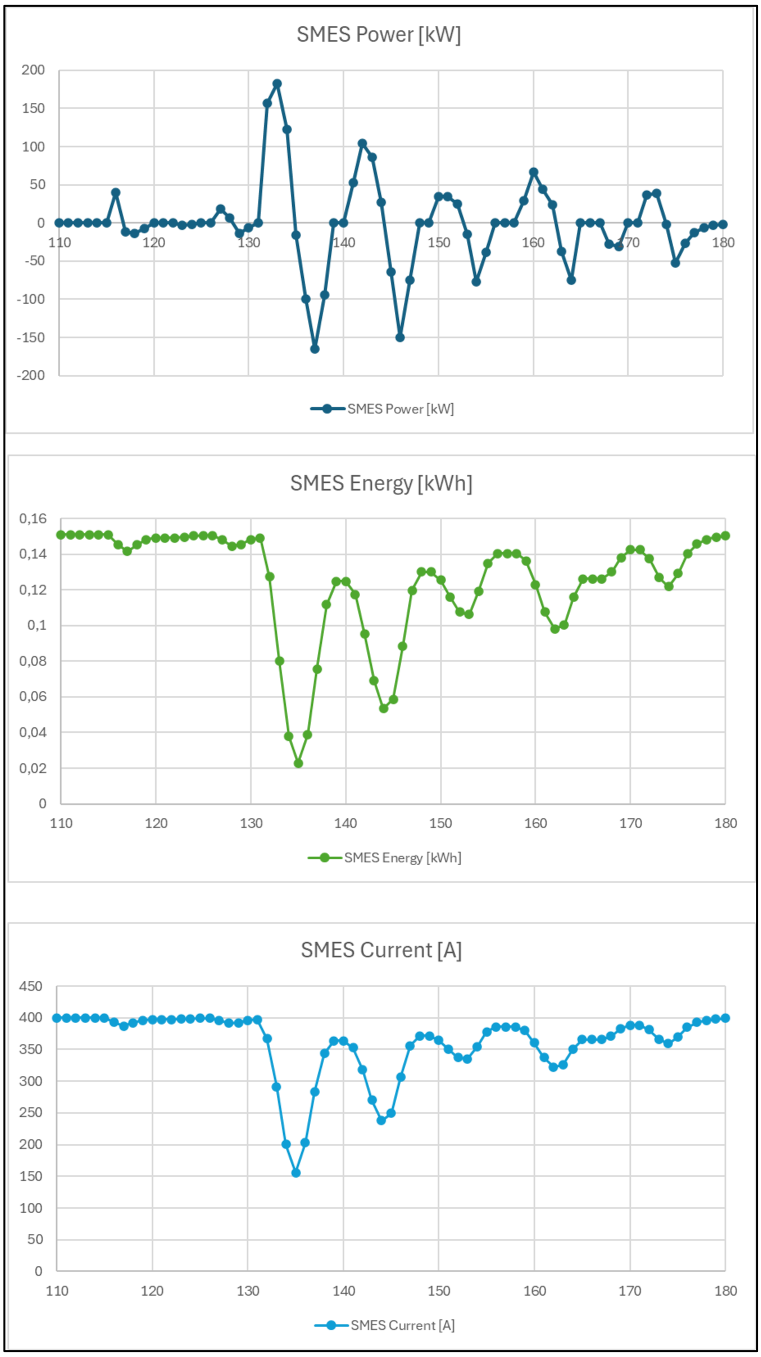


Figure 22: SMES power, energy and current curves in spinning reserve (OSV-AHC case)

3.1.3 SMES concept design case Trawler

Results from the study on the Trawler case are collected in Table 7: Power and energy distribution Trawler case.

The size of the SMES in this case is smaller, compared to the Ferry and OSV cases, in terms of current (max current 400A) and inductance.

Voltage of DC bus, V	750
Max current, A	400
Inductance, H	4
Total Energy, kJ	320
Total Energy, Wh	88.9

Table 19: Main parameters for SMES Trawler case.

3.2 Mechanical integration of SMES

3.2.1 SMES location case Electric Ferry

Location:

The locations of the SMES's for the electric ferry are in a separate room next to the BESS and Engine rooms at the forward and aft locations on the ferry like shown in the figure below.

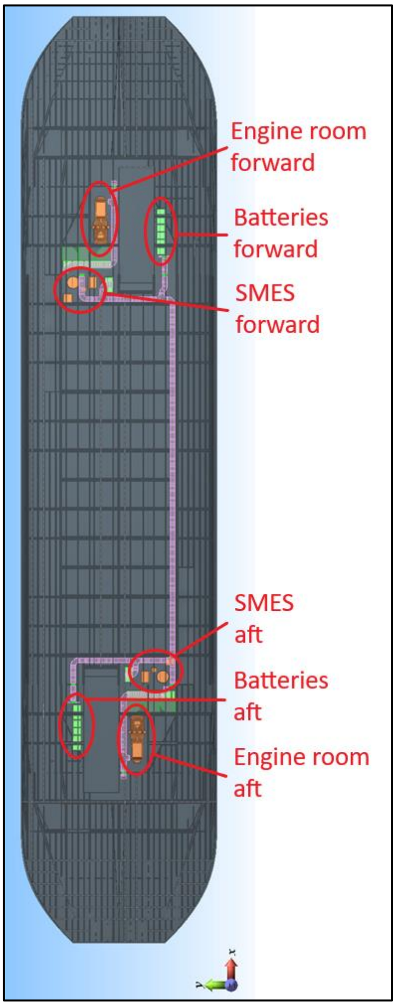


Figure 23: Positions of the forward and aft SMES rooms case Electric Ferry

Dimensions:

	Dimensions (mm)
Compressor	532x443x403
*Chiller**	*800x600x1000*
Vacuum pump	900x900x1150
Vacuum chamber + magnet+cryocooler	Diameter: 1200 H=2300
Power Electronics	850x850x2200

Table 20: SMES dimensions in case Electric Ferry

Weight:

	Weigth
Compressor	100 kg
*Chiller**	*100 kg*
Vacuum pump	5 kg
Vacuum chamber + magnet+cryocooler	700 kg
tot	900 kg with chiller
Power Electronics	200

Table 21: SMES weighs in case Electric Ferry

**Chiller could be optional if it exists on board the ferry*

3.2.2 SMES location case OSV-AHC

Location:

The ESS containing SMES in case OSV-AHC requires a larger space than available in the existing Energy Storage Room on the Tank Top deck on the vessel as shown with the green transparent area in the figure below.

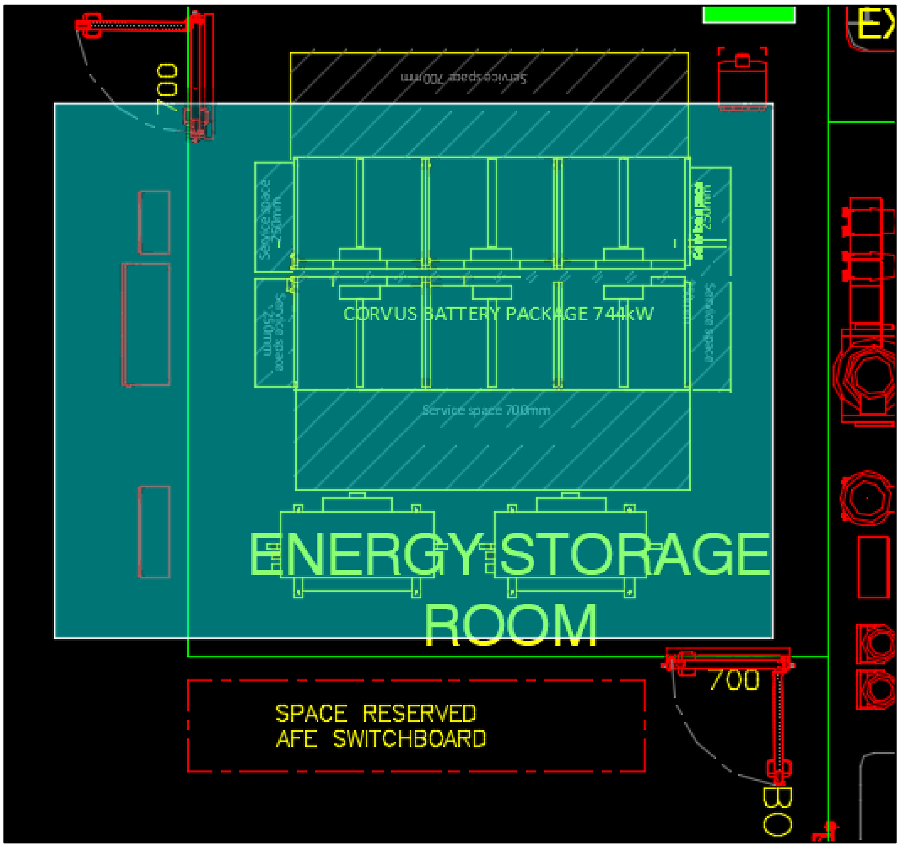


Figure 24: Illustration of SMES (green transparent) placed over ESS room in case OSV-AHC

Dimensions:

	Dimensions (mm)
Compressor	532x443x403
*Chiller**	*800x600x1000*
Vacuum pump	900x900x1150
Vacuum chamber + magnet+cryocooler	Diameter: 1200 H=2300
Power Electronics	850x850x2200

Table 22: SMES dimensions in case OSV-AHC

Weight:

	Weigth
Compressor	100 kg
*Chiller**	*100 kg*
Vacuum pump	5 kg
Vacuum chamber + magnet+cryocooler	700 kg
tot	900 kg with chiller
Power Electronics	200 kg

Table 23: SMES weights in case OSV-AHC

**Chiller could be optional if it exists on board the OSV*

3.2.3 SMES location case Trawler

Location:

The ESS containing SMES in case Trawler requires a larger space than available in the existing Battery Room on the vessel as shown with the green transparent area in the figure below.

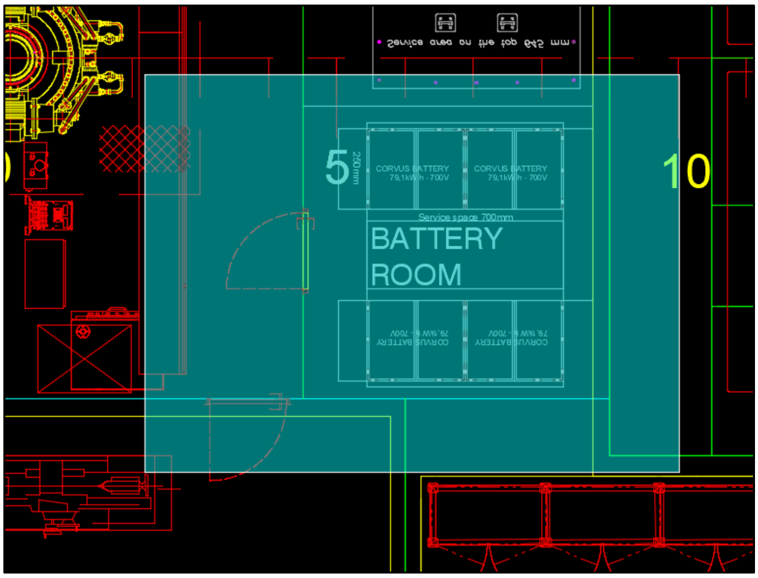


Figure 25: Illustration of SMES (green transparent) placed over ESS room in case Trawler

Dimensions:

	Dimensions (mm)
Compressor	532x443x403
*Chiller**	*800x600x1000*
Vacuum pump	900x900x1150
Vacuum chamber + magnet+cryocooler	Diameter: 700 H=1300
Power Electronics	850x850x2200

Table 24: SMES dimensions in case Trawler

Weight:

	Weigth
Compressor	100 kg
*Chiller**	*100 kg*
Vacuum pump	5 kg
Vacuum chamber + magnet+cryocooler	400 kg
tot	600 kg with chiller
Power Electronics	100 kg

Table 25: SMES weights in case Trawler

**Chiller could be optional if it exists on board the Trawler*

3.2.4 Installing the SMES components - all cases

The SMES system, as described in chapter 3.1 General description of SMES, is composed by 3 main parts: the SC unit (the magnet in its cryostat), the cooling system (the compressor and the chiller) and the power conditioning system.

The installation of the SMES system must comply with maritime regulations and classification of society standards for the actual vessel.

The compatibility with the ship's power system shall be verified at the designed stage, as well as the compatibility with the structural layout.

All the systems must be installed in designated compartments with services available (water and electricity). Specific damper could be required and installed on the external case of the systems.

Depending on the size, it may be required the installation of a fringe field shielding made of ferromagnetic steel to contain the magnetic field and to avoid magnetic fluctuation into the SMES room.

The installation of the SMES systems should be performed by qualified personnel employed or authorized, and the connection shall follow a scheme like the P&ID in the pictures (ref. Figure 20: PID scheme of the SMES system)

In the following pictures a schematic representation of a possible installation in a dedicated room. Note that the space is not fully optimized. This sketch is for the installation on land. Besides the SMES itself, it includes auxiliaries such as a chillier for the cold heads' compressor and the electric power converters that could be placed elsewhere according to the ship structure.

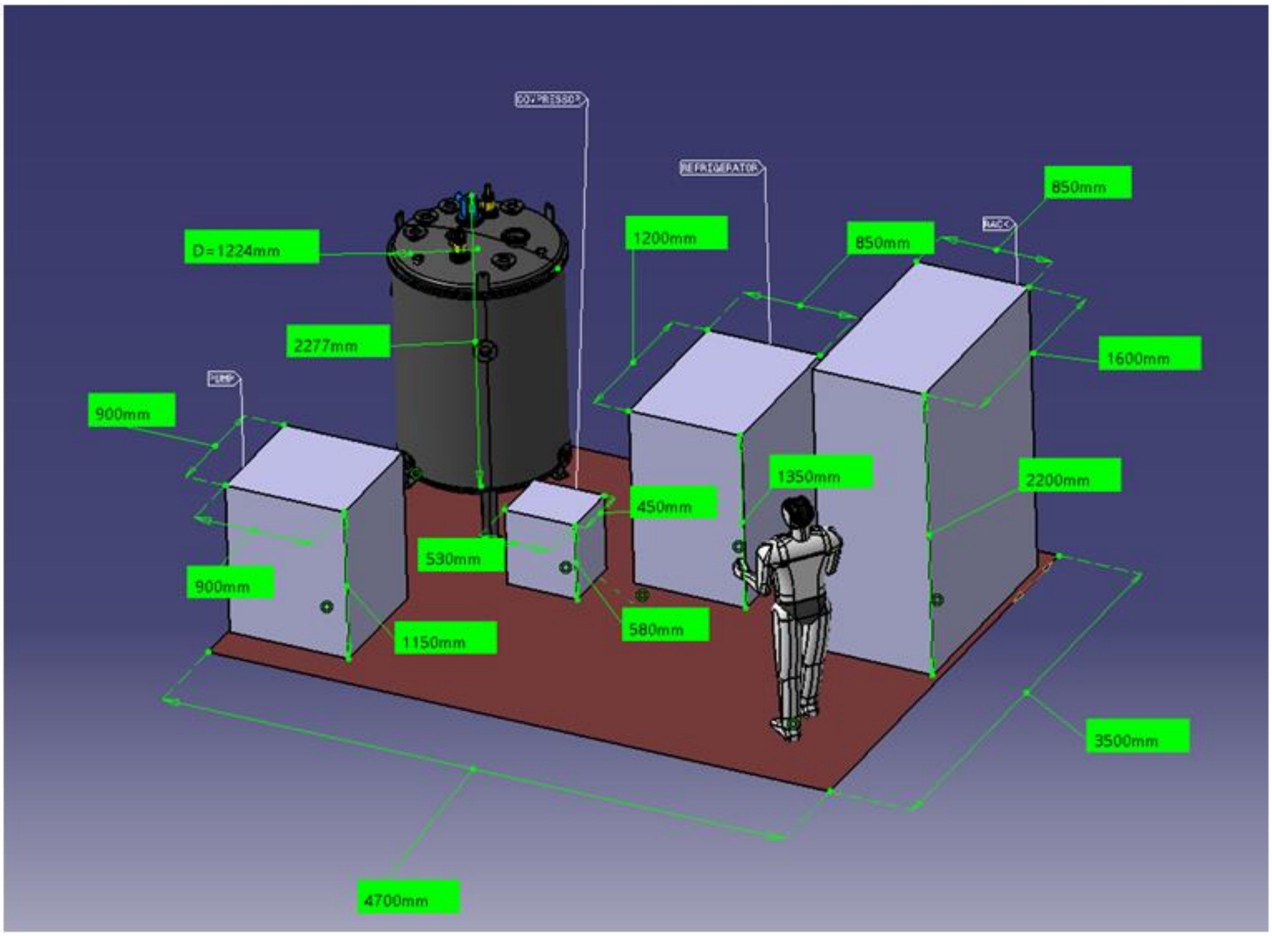


Figure 26: SMES component dimensions figure 1

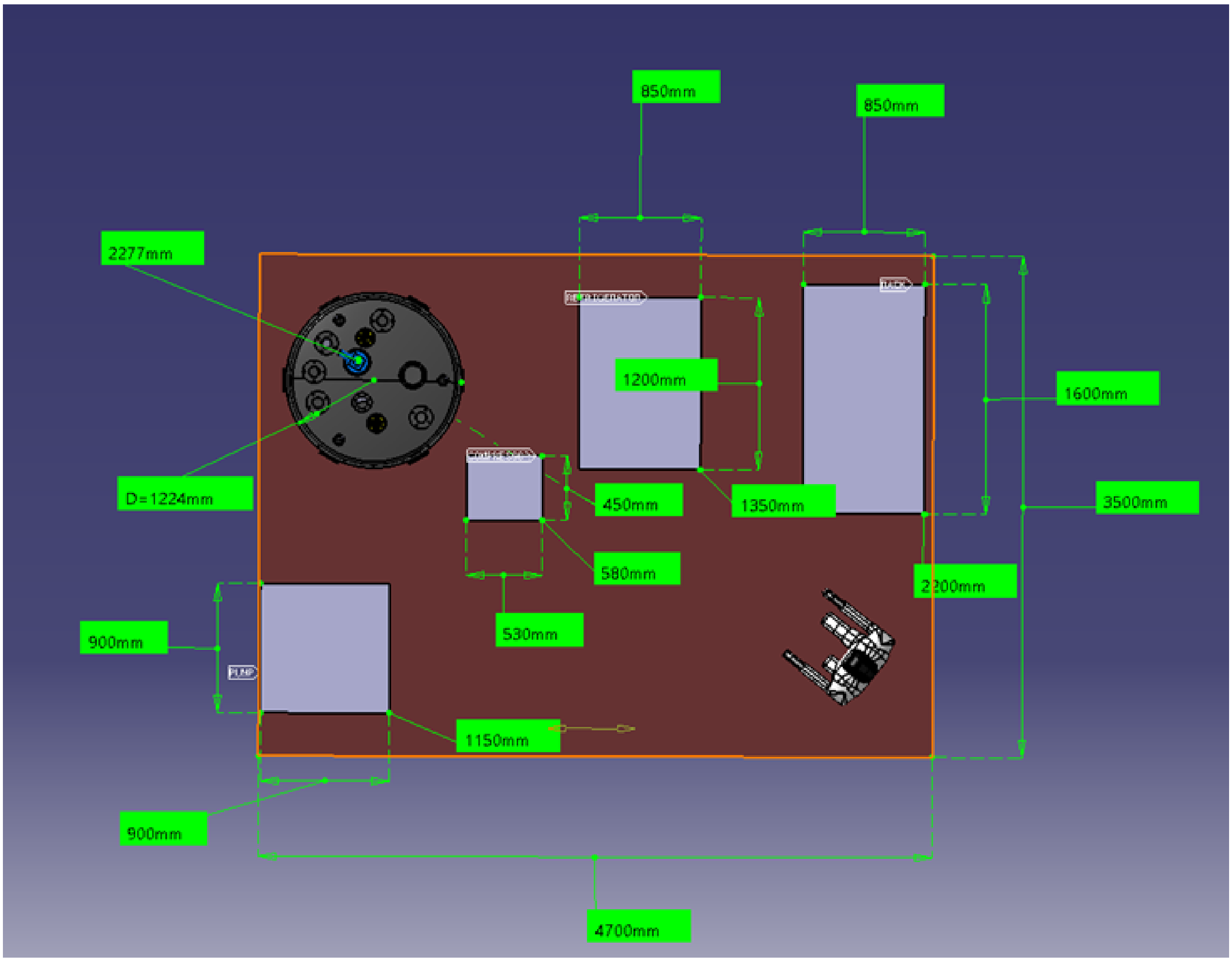
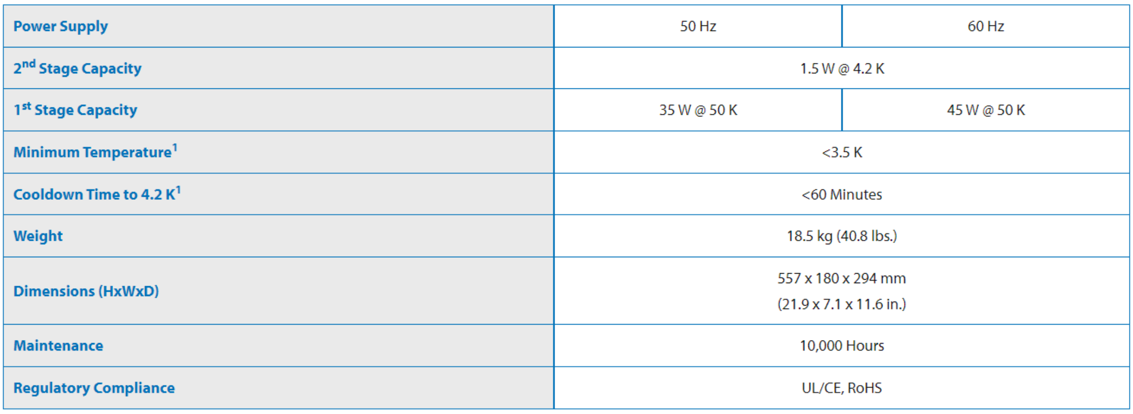


Figure 27: SMES dimensions figure 2

3.2.5 Cooling SMES - all cases

Considering the coil design with the characteristics as for the Ferry case and the specific application, the cryogenic solution is oriented towards a Gifford-Macmahon (GM) cryocooler. As an example, the performance of the Sumitomo RDK-415D2 is given (see specifications in Table 26 and cooling performance characteristics in Figure 28). This machine is intended to be used for the demonstrator in the V-ACCESS project.



Power Supply	50 Hz	60 Hz
2^{nd} Stage Capacity	1.5 W @ 4.2 K	
1^{st} Stage Capacity	35 W @ 50 K	45 W @ 50 K
Minimum Temperature[1]	<3.5 K	
Cooldown Time to 4.2 K[1]	<60 Minutes	
Weight	18.5 kg (40.8 lbs.)	
Dimensions (HxWxD)	557 x 180 x 294 mm (21.9 x 7.1 x 11.6 in.)	
Maintenance	10,000 Hours	
Regulatory Compliance	UL/CE, RoHS	

Table 26: Technical specification of the cryocooler selected for the SMES module

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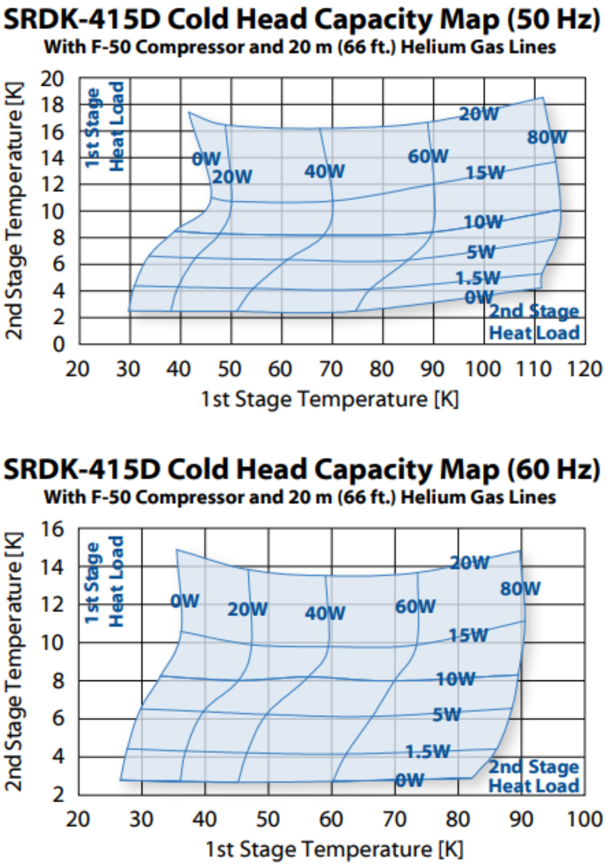


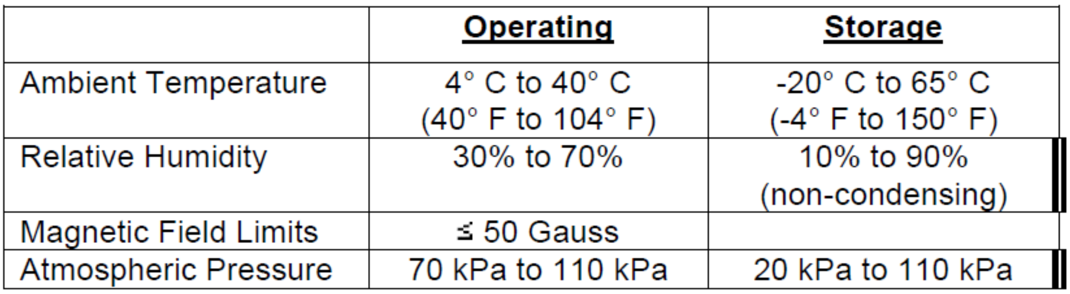
Figure 28: Capacity maps of the SRDK-415 cryocooler from Sumitomo.

To operate the cold head, the system is completed with the auxiliary gas compressor (Sumitomo F70L) with the main specification in Table 27.

	F-70LP	F-70L	F-70H
Electrical Supply[1]	3 Phase 200 V, 50/60 Hz		3 Phase 380-415 V, 50 Hz 480 V, 60 Hz
Power Consumption[2]	6.7-7.2 kW at 50 Hz 8.0-8.5 kW at 60 Hz	6.6-6.9 kW at 50 Hz 7.5-7.8 kW at 60 Hz	
Ambient Temperature[3]	4-40 °C (39-104 °F)		
Cooling Water (Inlet)	6-9 L/min. (1.6-2.4 gal./min.) 5-25 °C (41-77 °F)		
Dimensions(HxWxD)	532 x 443 x 493 mm (20.9 x 17.4 x 19.4 in.)		
Weight	100 kg (220 lbs.)		
Maintenance	30,000 Hours		

Table 27: Technical specification of the compressor for the cryocooler selected for the SMES module

There are some environmental requirements for the compressor that must be considered to achieve the correct performance, these are summarised in Table 28. These conditions can be guaranteed on board by placing the compressor in an air-conditioned container, if necessary. In addition to these requirements, the installation position should also be guaranteed, and a maritime on-board stabilisation system must be installed to guarantee a tilt of less than 5 degrees from the horizontal.



	Operating	**Storage**
Ambient Temperature	4° C to 40° C (40° F to 104° F)	-20° C to 65° C (-4° F to 150° F)
Relative Humidity	30% to 70%	10% to 90% (non-condensing)
Magnetic Field Limits	≤ 50 Gauss	
Atmospheric Pressure	70 kPa to 110 kPa	20 kPa to 110 kPa

Table 28: Ambient requirements for the compressor selected in the SMES module

For the safety of the operation 2 cold heads and their auxiliaries can be installed on board. It includes chillers.

3.2.6 Vibration SMES - all cases

The suspension system in general is one of the critical aspect aspects in superconducting magnets, since any component connecting the outer structure at room temperature to the cold SuperConducting coil is a source of thermal inlet. It increases the cryogenic energy consumption (thermal power or consumption of liquid or gaseous helium or liquid hydrogen for the coil or liquid nitrogen for the thermal shield.

During the design and development of the components of the suspension system, it is necessary to define precisely the mechanical loads that the system will have to withstand, in order to minimise the size and dimensions of the tie rods and at the same time to guarantee sufficient safety margins. It is desirable to use special materials with low thermal conductivity, such as Inconel, Titanium, Glass Fibre or a combination of these materials, as their mechanical resistance performance is good at cryogenic temperatures.

To suspend the SMES SuperConducting coil, if the installation is in a laboratory or in a building, upper vertical tie rods are generally sufficient to hold the coil in position at the centre of the cryostat. In land use, the mechanical loads are only the weight of the coil and the best solution is to adopt fibreglass reinforced polymer (FRP) tie rods, which have both high mechanical tensile performance and also of low thermal conductivity. As shown in Figure 2 below, this type of SMES application requires only a few and optimised number of tie rods, only four in this illustration, since the load is only in the vertical direction from the earth's gravity.

If a SMES is installed onboard a ship, the magnet is subjected to several additional 3D mechanical loads such as motions, accelerations and vibrations that are generated on-board. With this kind of loads, a more sophisticated suspension system must be designed.

The magnet must be fixed to resist to main stresses in all the directions. The tie-rods must be also preloaded (maintained under tensile stress) to guarantee the position of the coil in every mechanical solicitation.

A typical suspension system layout able to withstand this kind of stress is shown in the following schematic representation and it is composed by:

- Three upper vertical Tie-Rods that connect the Coil to the Upper Flange of the Cryostat Vessel
- Three lower vertical Tie-Rods that connect the Coil to the Lower side of the Cryostat Vessel to limit the flexion stress on the upper rods

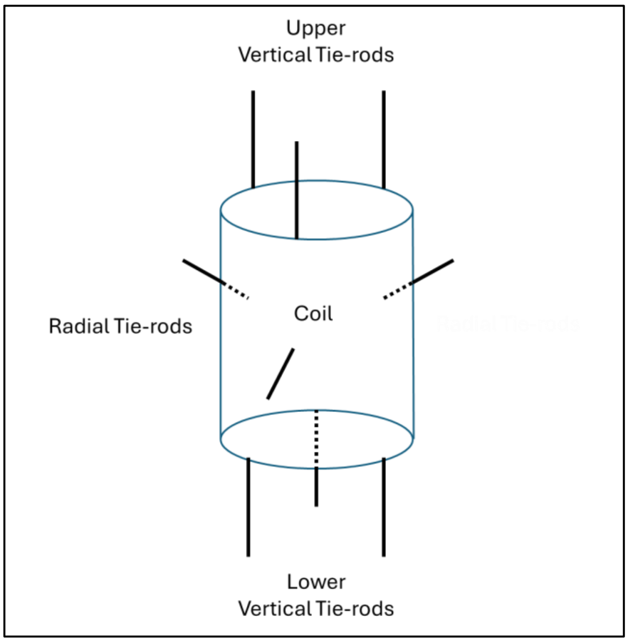


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Figure 29: Schematic representation of typical suspension system for SMES coil

3.2.7 EMC SMES - all cases

The energy in an SMES is stored in the magnetic field of a magnet. In a SuperConducting magnet, this can be high while maintaining relative compactness of the system: however, as a strong magnetic field is desirable for high energy storage, it generates a stray magnetic field that spreads from the cryostat around the SMES system. Equipment in the affected area must accept this magnetic field and operate safely. However, the magnetic field is quasi-stationary with only low frequency variations.

For the on-board application in the V-ACCESS project, we consider an SMES with a solenoid design. The SuperConducting coil is placed in cylindrical cryostats as shown in Figure 8 and its characteristics are shown in Figure 9. This SMES fits the "ferry case" studied in V-ACCESS, which was found to be the most demanding in terms of level energy storage.

As the field generated is mostly static, it does not cause induction or interference (only in case of specific devices, like sensors susceptible to DC magnetic field), However a check of the human exposure close to the system should be carry out. If we consider the data in figure 9 done for the Ferry case, it's possible to check that the line at 5gauss-0.5mT (where the hazard is just about the interference with implanted devices, e.g. cardiac pacemakers) is about 5 meter far from the coil, without any, or very small, variation of the field intensity with the height from the floor. The calculation shows that the SMES cryostat surface is at 1000gauss-0.1T, below the accepted limit for normal working conditions. The EMC will be measured in the type test procedure to check the IEC requirements.

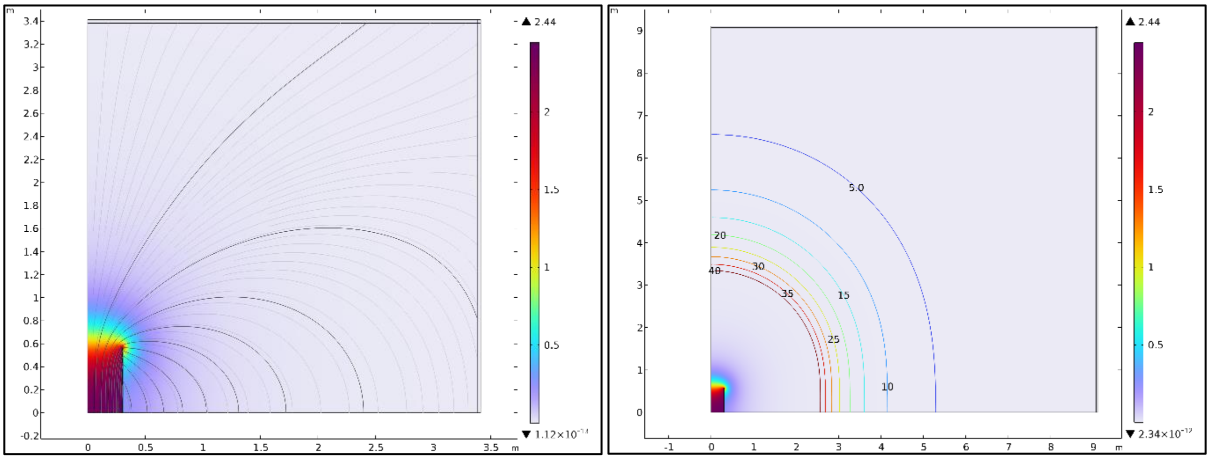

Figure 30: Magnetic field map evaluation around the SMES coil

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3.3 Electrical integration of SMES

The electrical integration of SMES is done by placing a DC-DC converter (see chapter 3.3.4 Description of integrating components for SMES – all cases) between each of the ESS's with SC and the DC switchboard in all the 3 vessel cases investigated.

The ESS with SMES is exchanging energy with the power plant through the DC-DC converters based on the control strategies described in chapter 4.1 for all 3 cases.

3.3.1 Electrical integration SMES case Electric Ferry

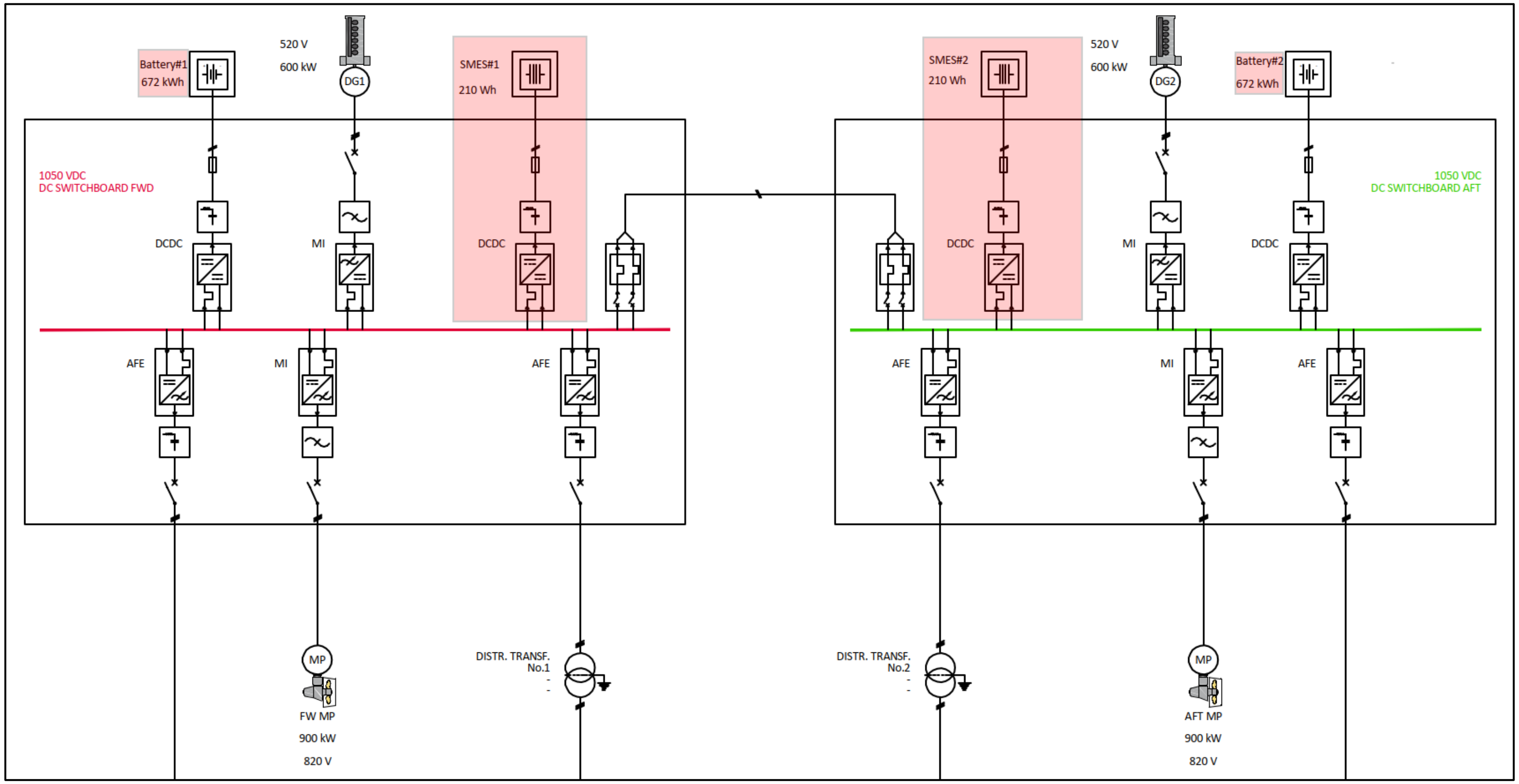

Figure 31: Single-Line-Diagram for case Electric Ferry with battery and SMES

3.3.2 Electrical integration SMES case OSV-AHC

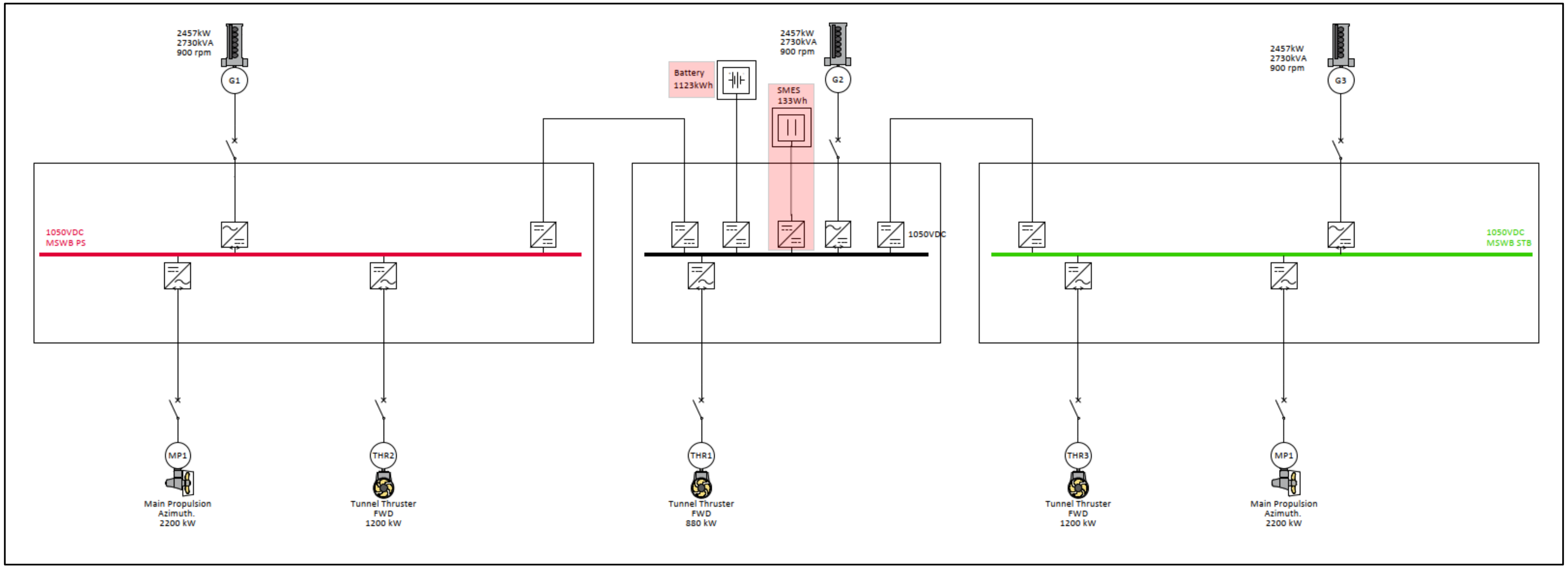

Figure 32: Single-Line-Diagram for case OSV-AHC with battery and SMES

3.3.3 Electrical integration SMES case Trawler

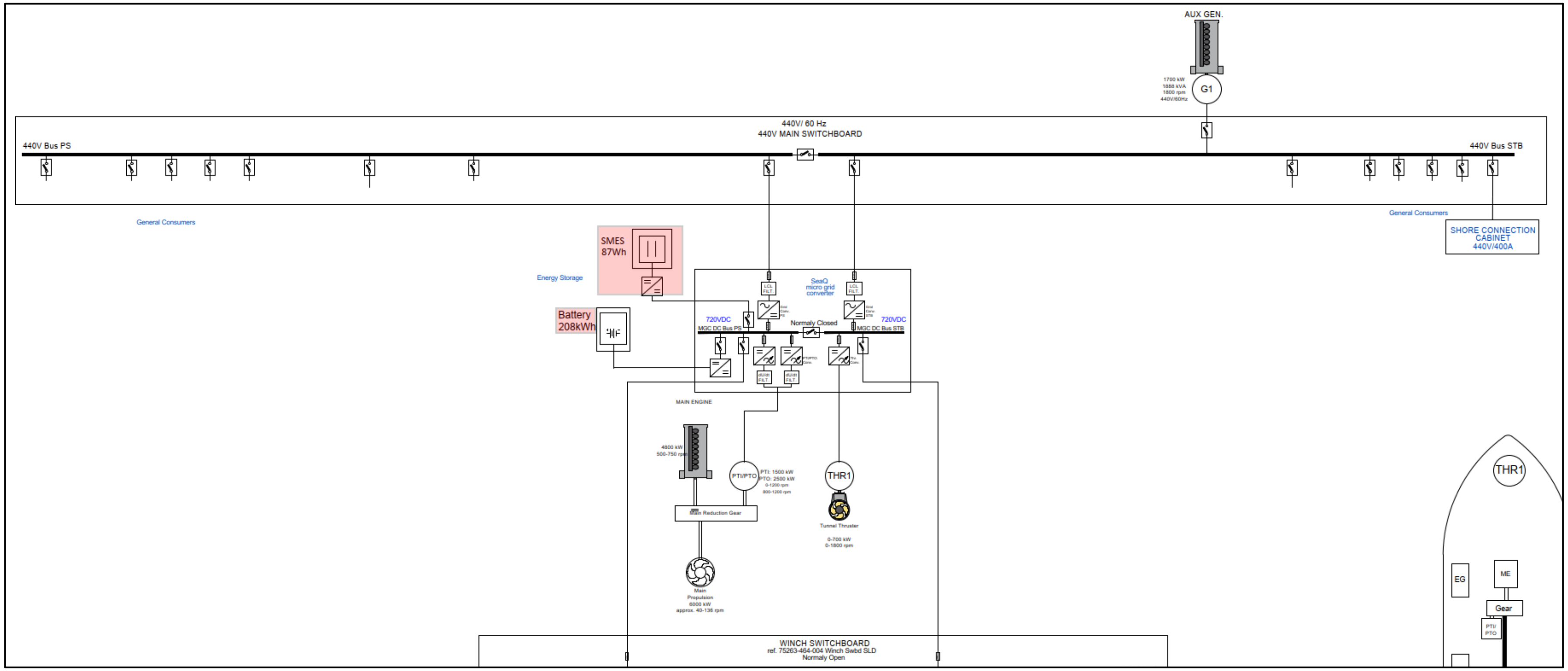

Figure 33: Single-Line-Diagram for case Trawler with battery and SMES

3.3.4 Description of integrating components for SMES – all cases

The topology of the DC-DC is a direct conversion system that interfaces the current source to the DC bus.

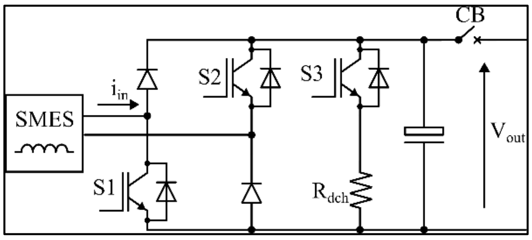

Figure 34: DC-DC converter topology for SMES

The converter controls the output voltage at a fixed value (operating, for the output port, as a voltage source). The converter implements the following input digital ports:

- a GPIO to enter *turn-off mode*.
- a button to enter *turn-on mode*.
- a GPIO to enter *turn-on mode*.

It also implements the following output digital ports:

- undercurrent on SMES detected.
- overcurrent on SMES detected.
- dedicated GPIO **and** LED indicating each operating mode.
- dedicated GPIO **and** LED indicating internal faults.

3.4 Safety for SMES

Recommendations from D5.3 Risk assessment analysis of ESS:

- No interconnection of the ventilation ducts between the compartment containing the SMES and the rest of the vessel.
- To have an emergency shutdown for this ventilation from a remote location.
- Manual activation capability of fi-fi system from a remote location.
- External fire-fighting system for electrical fires.

4 Control System Integration

Integration of an ESS with SC or SMES into the control system onboard a vessel is necessary to be able to utilize these new devices.

4.1 Control strategies

4.1.1 Fully electric – batteries only

In fully electric operation on only batteries, they must be in charge of the voltage, hence the DCDC will be operating in voltage control. SoC balancing of the batteries can be done in two different ways. Adjusting the output voltage of the DCDC converter according to SoC, increasing the voltage on the one with higher SoC and reducing the voltage on the one with lower SoC. The other possibility is to adjust the DC voltage droop curves during operation, reducing the droop on the one with higher SoC and increasing the droop on the one with lower SoC.

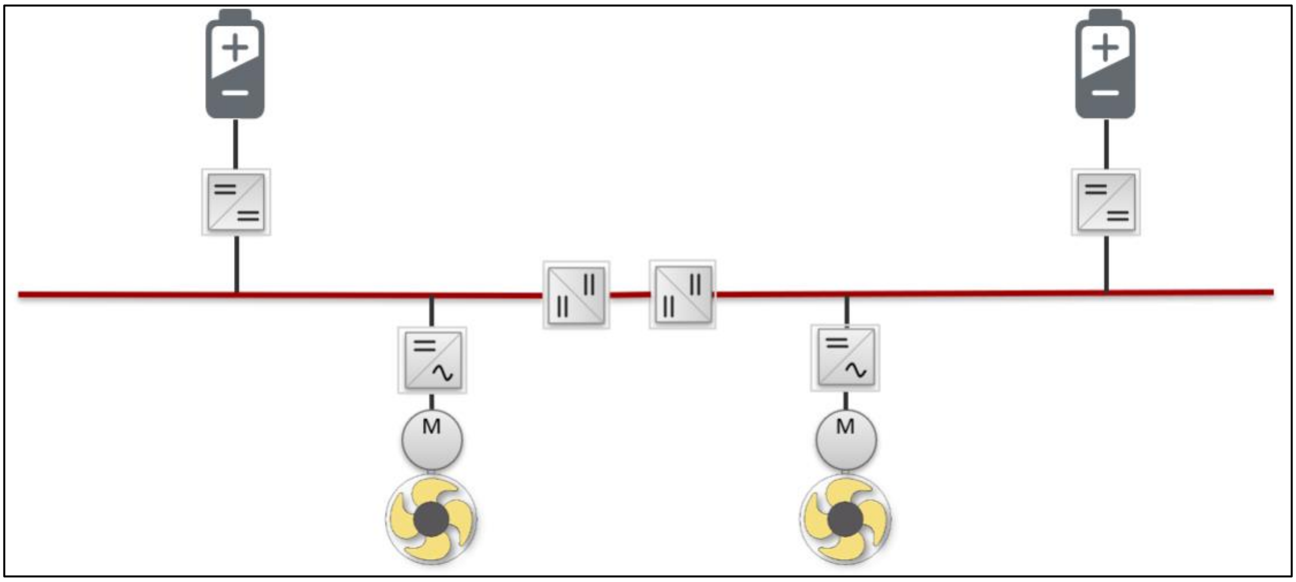

Figure 35: Fully electric – batteries only

4.1.2 Fully electric – SC/SMES and batteries

In fully electric operation the SC/SMES can be in charge of the voltage, hence the DCDC will be operating in voltage control, while the DCDC for the batteries can be operated in power control. SoC balancing between the SCs/SMES can be done in two different ways. Adjusting the output voltage of the DCDC converter according to SoC, increasing the voltage on the one with higher SoC and reducing the voltage on the one with lower SoC. The other possibility is to adjust the DC voltage droop curves during operating, reducing the droop on the one with higher SoC and increasing the droop on the one with lower SoC.

As the DCDC for the batteries are operated in power control the control system must make sure that the batteries contribute to the load sharing before the SCs/SMES reaches maximum power outtake. The setpoint to the regulator could for example be the average baseload (hotel and variable consumer) of the system. The baseload can be found by summating power going towards the DC grid from the battery and SC/SMES. Another possibility is to use the average power from/to the SC/SMES as input to the regulator, with a setpoint of zero – making the batteries take over the load from the SC/SMES. If the SoC of the SC/SMES goes too high or too low an offset could be added to the regulator setpoint, bringing the SoC within the desired range again. SoC balancing between the batteries can be done by looking at the average SoC between the two systems and compensating for the difference to the power references. The batteries should normally not be used to recharge the SCs/SMES, since they are intended to charge when the load demand is reduced.

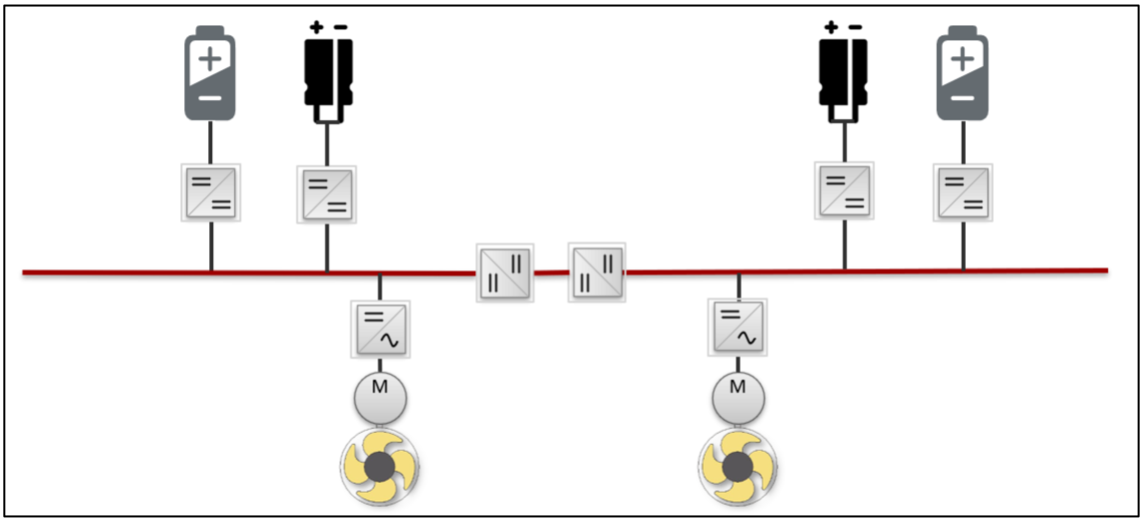

Figure 36: Fully electric – batteries and SC/SMES

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4.1.3 Hybrid – diesel generators, batteries and SC/SMES

An assumption is made on the converters for the diesel generators. It is assumed that they are active front end (AFE) converters and not just a diode bridge. A diode bridge could be chosen, but this have some pros and cons. Pros is that it is somewhat more efficient due to the elimination of switching losses and the hardware is cheaper and more compact. Cons are that it makes the control much harder since it would mean that the automatic voltage regulators would have to be actively controlled. Additionally, the output voltage of the generator must be high enough to be able to produce the desired DC voltage.

The diesel generators DGs can be set to fixed power control while the control strategy for the battery and SC/SMES can remain the same as described in Fully electric – SC/SMES and batteries (trying to achieve zero power to/from the SCs/SMES). The DGs can either be set to produce the average baseload or a fixed power at an efficient setpoint, according to the specific fuel oil curve (SFOC). If the SoC of the batteries increases too much a DG can be stopped or variable speed control of the DG could be added to allow the DG to work efficiently over a wider power range.

Possible simplification: The diesel generators are foreseen to be used in emergencies or when there is a failure to the onshore charging station. The diesel generators provide the power system with a higher capacity so the SC/SMES can be taken out to simply the control strategy. In this setup the DCDC converters of the batteries can be set to DC voltage control while the generators are set to produce fixed power. The power setpoint to the AC/DC converters for the generators can be selected according to the specific fuel oil curve (SFOC) to produce power efficiently. Power setpoint to be changed if the SoC of the batteries are either increasing or decreasing too much. Variable speed and starting/stopping DGs is also an option here.

For the trawler case, the above explained solution can be utilized in parallel with the main engine connected to the DC switchboard through the reduction gear and motor. In situations where the auxiliary generator is not connected the grid converters must be in AC voltage control to power the AC grid. In the trawler case there are a few more varieties of setups that can be utilized, affecting the control strategy. Such as the operation of the auxiliary engine. The auxiliary engine is connected if the power demand for the main engine is too high, hence the motor will be operated in power transmission input mode where it is no longer a generator, but a load. At this point the grid converters will be responsible for the DC voltage, making the auxiliary engine hold the base load while the batteries and SC does peak shaving and boosting.

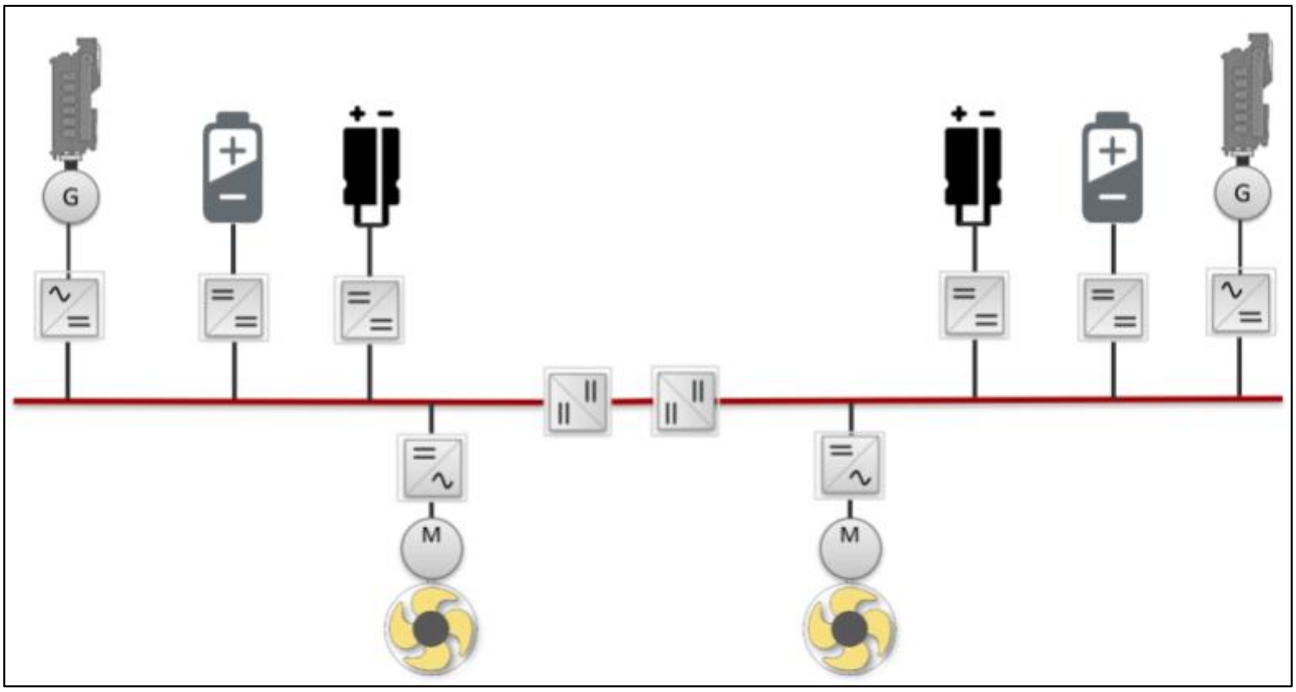

Figure 37; Hybrid – diesel generators, batteries and SC/SMES.

4.1.4 Applicable control strategies for the 3 cases

Case Electric Ferry:

- Can apply all the strategies presented above.

Case SOV-AHC:

- The main control strategy will be hybrid, due to limited energy reserves and redundancy capabilities of the energy storages. The other control strategies can be applied but for a very limited period.

Case Trawler:

- The main control strategy will be hybrid, due to limited energy reserves of the energy storages. The other control strategies can be applied but for a very limited period.

The goal for the selected control strategy in all 3 cases is to use ESS's with SC/SMES in addition to the existing BESS to extend the lifetime of the batteries. This must be done by using the ESS's with SC/SMES to handle the power peaks.

4.2 Energy Management System (EMS) integration

Figure 38: HMI for the Energy Management System (EMS) from Vard Electro

The ESS's with SC or SMES will be connected to the Energy Management System (EMS) onboard the vessel just as another generator as shown in Figure 38 above.

The control strategies (algorithms) to be implemented in the EMS to control the usage (charging/discharging) of the ESS's with SC an SMES are described chapter 4.1.

When an ESS with SC or SMES is installed onboard a vessel some tuning of the EMS will be required.

The interfaces requirements (e.g. physical, protocols, etc.) between the ESS with SC or SMES and the control system must be agreed. Normally this takes place an "interface meeting" with the partners when a vessel is being built or modified.

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4.3 Status and alarms

Figure 39 below shows the EMS HMI for status and alarms for a BESS.

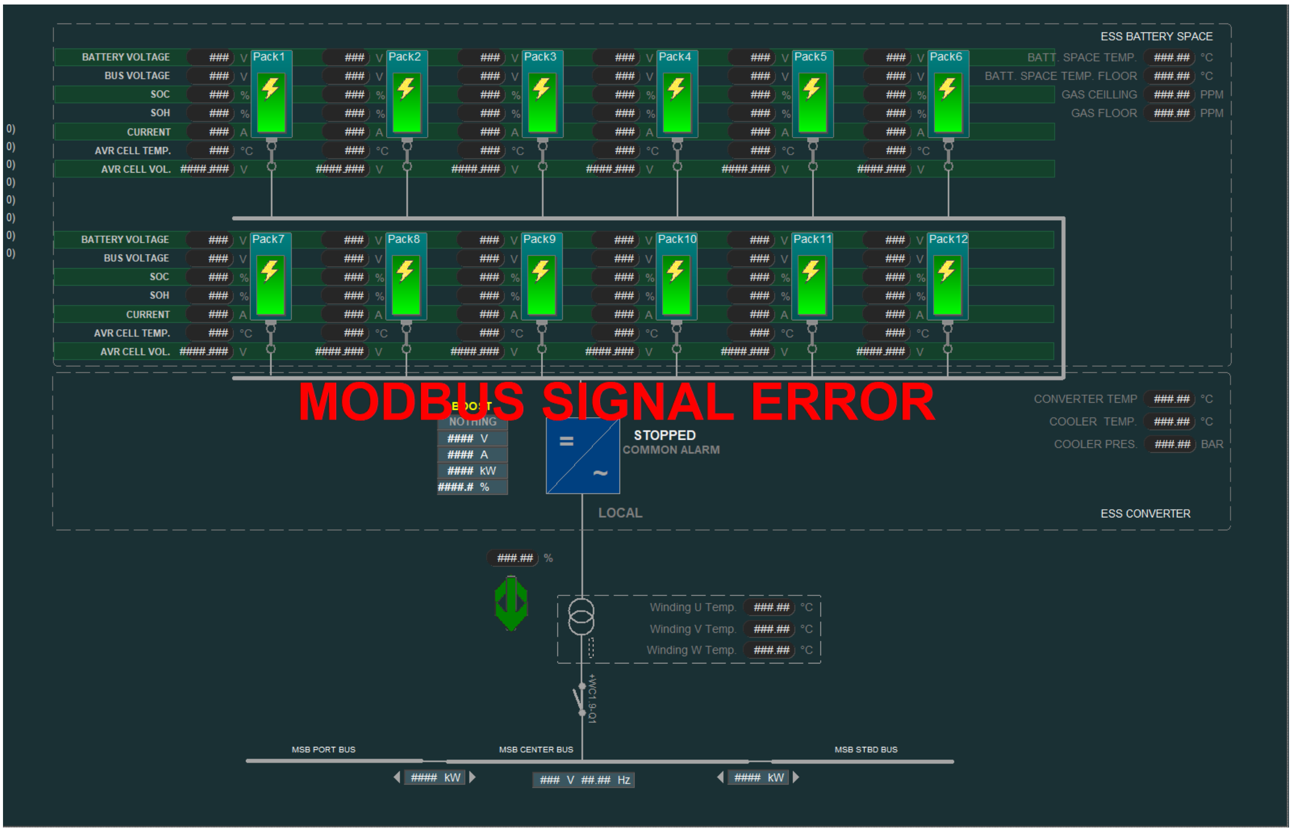

Figure 39: HMI for the EMS for a BESS

The EMS HMI status and alarms for ESS's with SC and SMES will look about the same as for the BESS above.

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4.3.1 Status and alarms from SC

The following status and alarms for an ESS with SC will be shown in the HMI of the EMS:

Parameter	Offset	Bits	Range/Values	Value offset
Operational state	0	4	0 - Enumeration 1 - Standby 2 - Precharge 3 - Operational 4 - Discharge 5 - Fault	
Reserved	4	1		
Reserved	5	1		
Reserved	6	1		0
Module missing	7	1	0 - Inactive 1 - Active	0
Module configuration error	8	1	0 - Inactive 1 - Active	0
Module communication error	9	1	0 - Inactive 1 - Active	0
High temperature alarm = reaching safety limit imminent	10	1	0 - Inactive 1 - Active	0
High temperature safety limit exceeded	11	1	0 - Inactive 1 - Active (latched)	0
High voltage alarm = reaching safety limit imminent	12	1	0 - Inactive 1 - Active	0
High voltage safety limit exceeded	13	1	0 - Inactive 1 - Active (latched)	0
Contactor feedback error	14	1	0 - Inactive 1 - Active	0
Switchgear fault	15	1	0 - Inactive 1 - Active	0
HV disconnected alarm	16	1	0 - Inactive 1 - Active	0
Fuse tripped alarm	17	1	0 - Inactive 1 - Active	0

Cooling failure	18	1	0 - Inactive 1 - Active	0
Unbalanaced cell voltage alarm	19	1	0 - Inactive 1 - Active	0
Reserved	20	1		0
Date/time missing	21	1	0 - Inactive 1 - Active	0
Internal storage failure	22	1	0 - Inactive 1 - Active	0
Module daisy-chain open-wire	23	1	0 - Inactive 1 - Active	0
Reserved	24	1		0
Cell open-wire	25	1	0 - Inactive 1 - Active	0
Module status error	26	1	0 - Inactive 1 - Active	0
Hardware failure	27	1	0 - Inactive 1 - Active	0
Module storage failure	28	1	0 - Inactive 1 - Active	0
Sense error	29	1	0 - Inactive 1 - Active	0
Low voltage alarm = reaching safety limit imminent	30	1	0 - Inactive 1 - Active	0
Reserved	31	1		0
High current alarm = reaching safety limit imminent	32	1	0 - Inactive 1 - Active	0
High current safety limit	33	1	0 - Inactive 1 - Active (latched)	0
Reserved		...	0	
Message counter	60	4	0..15	0

4.3.2 Status and alarms from SMES

The following status and alarms for an ESS with SMES will be shown in the HMI of the EMS:

Description	Data type	Scale	Unit	Information
ESS In Remote Control	BOOL	"1:1"	Status	
ESS Ready	BOOL	"1:1"	Status	
ESS Starting	BOOL	"1:1"	Status	
ESS Stopping	BOOL	"1:1"	Status	
ESS Precharging	BOOL	"1:1"	Status	
ESS Running	BOOL	"1:1"	Status	
ESS Boost Active	BOOL	"1:1"	Status	
ESS Anti Boost Active	BOOL	"1:1"	Status	
ESS Start Blocked	BOOL	"1:1"	Status	
ESS Common Alarm	BOOL	"1:1"	Alarm	
EtherCAT Slave Communication Error	BOOL	"1:1"	Alarm	
ESS Local Operation Panel Communication Error	BOOL	"1:1"	Alarm	
ESS Local Monitor Communication Error	BOOL	"1:1"	Alarm	
Start Timeout	BOOL	"1:1"	Alarm	
Transformer Hi Temperature	BOOL	"1:1"	Alarm	
ESS Shutdown	BOOL	"1:1"	Fault	
Emergency Stop Activated	BOOL	"1:1"	Fault	
ESS Breaker External Trip	BOOL	"1:1"	Fault	
Transformer HiHi Temperature	BOOL	"1:1"	Fault	
SMES Room Fire Alarm	BOOL	"1:1"	Fault	
SMES Room Fire Suppression Released	BOOL	"1:1"	Fault	
ESS Nominal Power	UINT	"1:1"	kW	Nominal power of the ESS
SMES Discharge Power Limit	INT	"1:1"	kW	Discharge limit for the ESS system (considers power source minimum load)
SMES Charge Power Limit	UINT	"1:1"	kW	Charge limit for the ESS system
SMES Power Available	UINT	"1:1"	kW	Available power from the battery

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SMES Available Energy	UINT	"1:1"	kWh	Available energy from the battery
SMES Remaining Battery Time at Max Rating	UINT	"1:1"	min	Remaining time at max rating
SMES Remaining Battery Time at Current Load	UINT	"1:1"	min	Remaining time at the current load
SMES Space Ambient Temperature	INT	"10:1"	°C	
Converters Active Current	INT	"1:1"	A	
Ready	BOOL		Status	
Running	BOOL		Status	
Ready	BOOL	"1:1"	Status	
Running	BOOL	"1:1"	Status	
Alarm Active	BOOL	"1:1"	Alarm	
Fault Active	BOOL	"1:1"	Alarm	
Communication Error	BOOL	"1:1"	Alarm	
Leakage Detected	BOOL	"1:1"	Alarm	
SMES cryogenic coil temperature at several points	INT	"10:1"	K	
SMES cryogenic coil temperature at several points	bool	"1:1"	alarm	
SMES room oxygen content	INT	"10:1"	%	
SMES room oxygen content	bool	"1:1"	alarm	
SMES auxiliary cryogenic cooling system	bool	"1:1"	alarm	
SMES cryostat vacuum level	INT	"10:1"	mbar	
SMES cryostat vacuum level	bool	"1:1"	alarm	
SMES electrical fault inside the coil (short circuit)	bool	"1:1"	alarm	
SMES RT connection of current leads temperature (x2)	INT	"10:1"	°C	
SMES RT connection of current leads temperature	bool	"1:1"	alarm	
SMES temperature of the cold end connection of current lead (x2)	INT	"10:1"	K	
SMES temperature of the cold end connection of current lead (x2)	bool	"1:1"	alarm	
SMES Superconductor quench detector	bool	"1:1"	alarm	

5 Conclusions

This study of interface requirements and standardization of the integration of ESS's with SC and SMES into the 3 vessel cases selected in the V-ACCESS project shows that there will be a need for some engineering work to be done for each installation onboard a vessel. The requirements are separated into 4 areas of integration:

1. Mechanical integration:
   For each vessel case there is a need to design in a proper location for the equipment to be installed. This location requirements according to the rules and regulations for the vessel type must be accommodated.

2. Electrical integration:
   The needed capacity of the electrical connection between the ESS's with SC and SMES must be identified, and a suitable integrating component (DC-DC or DC-AC converter) that fulfils the power requirements must be selected. All new components must then be added to the electrical Single-Line-Diagram for the vessel.

3. Safety:
   Necessary safety requirements for ventilation, firefighting and redundancy need to be accommodated and installed depending on the type of vessel and purpose of the ESS with SC or SMES.

4. Control system integration:
   The new ESS's with SC and SMES need to be integrated into the control system on the vessel. The control strategy to utilize the new ESS's needs to be implemented in the control system and the status and alarms from the ESS's need to be presented in the HMI for the control system. Interfaces requirements (e.g. physical interface, protocols, etc.) between the ESS with SC or SMES and the control system must be agreed.

Because of the complexity of the process of building a vessel and the rules that applies for the vessel type there are normally a lot of detailed engineering that needs to be done for all systems to be installed onboard.

To standardise an ESS solution with SC or SMES to be install onboard a vessel will require everything needed for the installation to be in a separate container to be placed e.g. on deck on the vessel. This will minimise the work on mechanical integration, electrical integration and safety. There will still be some work to be carried out to integrate the new ESS into the control system. This solution is normally only acceptable when retrofitting an ESS onto a vessel and not on a new build.