

D5.5 Teaching Material and Handbook for The Training Programmes

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This manual is intended for technicians, crew members, and system operators involved in the maintenance and operation of the Supercapacitor Energy Storage System (SESS) and Superconducting Material Energy Storage System (SMESS)

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1 Fundamentals of Supercapacitor Energy Storage (SCES) System

1.1 Introduction

A typical capacitor is made of two conductive plates with a dielectric material in between them, as shown in Figure 1. When a voltage is applied across these plates, positive and negative charges build up on each side, referred to as positive or negative electrodes. Even when the voltage is removed, the charges stay on the plates, allowing the capacitor to store energy. The stored energy will discharge if an electric wire or load is connected between these plates. Hence, the capacitors are capable of energy storage and discharge.

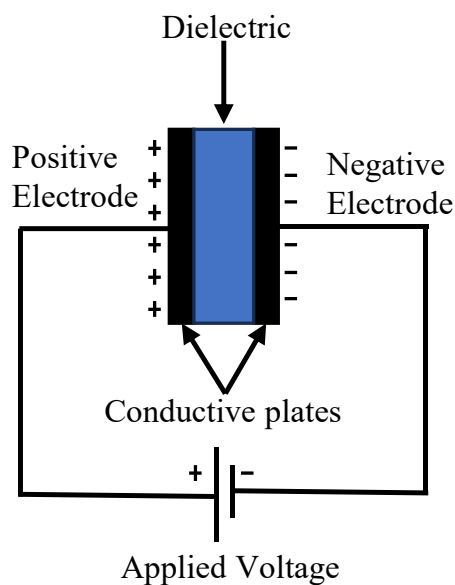


Figure 1: A typical capacitor structure connected to the supply voltage.

1.1.1 Basic types of Capacitors

The electrostatic and electrolytic capacitors are the basic types of capacitors. The electrostatic capacitor uses a solid dielectric such as ceramic, mica, plastic film, paper or air. On the other hand, an electrolytic capacitor uses an electrolyte dielectric such as tantalum. The solid dielectric cannot be polarised, while the electrolyte can be polarised, so the electrostatic and electrolytic capacitors can also be called non-polarised and polarised capacitors. These capacitors can only hold a lower capacitance in the range of picofarads to hundreds of millifarads. Beyond these basic types, an advanced category of capacitor is a supercapacitor or ultracapacitor, also known as an electric double-layer capacitor (EDLC).

1.1.2 Supercapacitors / Ultracapacitors / Electric Double-Layer Capacitors

Supercapacitors store significantly more energy per unit volume and mass than conventional capacitors. The name supercapacitor comes from the superiority of the capacitance as compared with traditional capacitors.

They exhibit capacitance values that are several orders of magnitude higher than those of conventional capacitors for comparable device volumes. Alternatively, it's called an EDLC [1], which is due to its physical structure as shown in Figure 2. The supercapacitor's internal structure is different from compared of a typical capacitor due to the presence of a separator between electrodes that forms a double layer. The separator is a porous membrane that allows the ions to pass while stopping electrical contact between electrodes. These electrodes are usually made of carbon-based active materials, providing a large surface area [2].

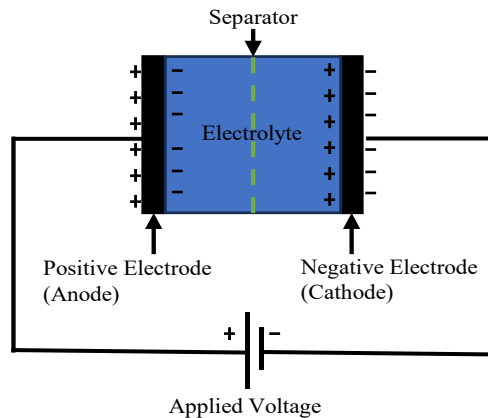


Figure 2: A structure of EDLC connected to the supply voltage.

The supercapacitor uses electrolytes and constructive elements depending on the desired application characteristics, such as power density, energy density, and operating voltage. Skeleton Technologies patented SkelCap ultracapacitor cells that use carbon composite electrodes with high energy density. It also highlighted that the use of carbon electrodes is important to achieve lower internal resistance[3].

1.1.3 Supercapacitor Equivalent Circuit Model

Resistive and capacitive elements can characterise a supercapacitor equivalent circuit model to represent its behaviour in an electrical circuit. In the basic electrical model of a supercapacitor, an equivalent series resistor is connected in series with two resistor-capacitor (RC) branches [4], as shown in Figure 3.

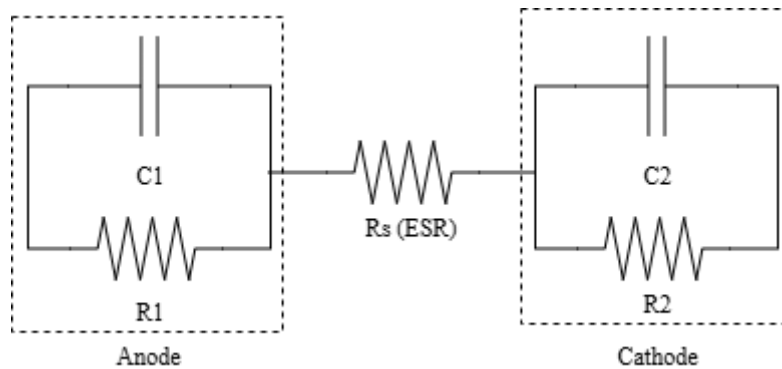


Figure 3: An Equivalent circuit model of a supercapacitor.

Where R1 and C1 represent the leakage resistance and capacitance of the positive electrode, R2 and C2 represent the leakage resistance and capacitance of the negative electrode, and Rs represent the equivalent series resistance (ESR). The individual leakage resistors of both electrodes are neglected, and the capacitors are combined into an equivalent single capacitor (Ceq) to simplify the electrical circuit model. The simplified supercapacitor model is represented by a resistor and a capacitor connected in series, as shown in Figure 4.

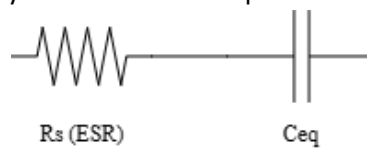


Figure 4: Simplified Equivalent circuit model of a supercapacitor.

1.2 Electrical properties of Supercapacitor

1.2.1 Charge

The amount of electrical energy stored in a supercapacitor when an external voltage is applied to the electrodes is called charge.

$$Q = C V \quad (1)$$

1.2.2 Capacitance

The ability of a supercapacitor to store energy per unit voltage is known as its capacitance, simplified in (2). It depends on the dielectric materials, the distance between the conductive plates, and the size of the plates.

$$C = \frac{Q}{V} \quad (2)$$

Where C is the capacitance in farads (F), Q is the charge stored in coulombs, and V is the voltage applied across the capacitor.

1.2.3 Energy Storage

The supercapacitor stores energy in the form of electrostatic and electrochemical mechanisms. The EDLC has an electrostatically large surface area where it stores the energy in the carbon electrode surface. The energy stored in a supercapacitor is given by:

$$E = \frac{1}{2} C V^2 \quad (3)$$

However, in real-world applications, the stored energy is expressed in watt-hour (Wh), as the datasheet of Skeleton SkelMod 102V 88F shows can be expressed as:

$$E = \frac{C V^2}{2 \times 3600} \quad (4)$$

where E is stored energy in joules (J), C is capacitance in farads (F), and V is the applied voltage across the supercapacitor terminal in volts (V).

1.3 Supercapacitor Charging and Discharging

Supercapacitors store and release energy in the process of charging and discharging. The energy is directly proportional to the capacitance and the square of the voltage. A variable power converter is essential to manage the energy transfer during both processes. For example, during charging, a power converter can be connected to charge the supercapacitor. Initially, it works in constant current mode for quick charging, while it changes to constant voltage mode when the supercapacitor voltage reaches its nominal voltage to provide over-voltage protection. The initial current limit is essential, otherwise, the supercapacitor can draw a huge inrush current due to its very low ESR, which can potentially damage the converter or supercapacitor. During discharge, the voltage of the supercapacitor drops with time while the current depends on the load and converter current limits. If the required output power is constant, then the supercapacitor discharging current will rise as the voltage drops to keep the stable output power.

1.4 Configuration of Supercapacitors in Circuits

Supercapacitors are commonly used in applications that require transient or fast response of charge and discharge cycles. However, the voltage of a single supercapacitor cell is usually low (typically 2.5-3V), which cannot meet the practical application requirements. In practice, multiple supercapacitor cells are connected in series and parallel combinations to create modules that meet the specific power requirements. Additionally, these modules require a balancing circuit, a protection system and a cooling system for their efficiency and reliability during operation. The balancing circuit is required to equally distribute the voltage across series-connected cells. The balancing process gives safe, functional and efficient utilisation of module capacity. The protection circuit objective is to protect the system from overcurrent, overvoltage, and short circuit. The cooling system is required for temperature control, as the capacitors produce heat due to high transient power flow.

1.5 Series Connection of Supercapacitors

Supercapacitors can be connected in series to increase the voltage while considering the decrease in capacitance. The series connection is represented in Figure 5.

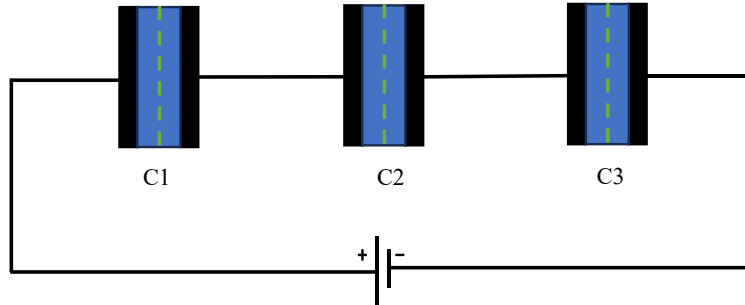


Figure 5: Supercapacitors series connection.

Total voltage and capacitance for the n number of series-connected supercapacitors are:

$$V_{total} = V_1 + V_2 + \dots + V_n \quad (5)$$

$$\frac{1}{C_{total}} = \frac{1}{C_1} + \frac{1}{C_2} + \dots + \frac{1}{C_n} \quad (6)$$

If the parameters (voltage, capacitance) of the individual supercapacitor cell are the same, then the voltage and capacitance become:

$$C_{total} = \frac{C_1}{n} \quad (7)$$

$$V_{total} = n \times V \quad (8)$$

1.6 Parallel Connection of Supercapacitor

Opposite to the series connection, the supercapacitors can be connected in parallel combination to provide increased capacitance while keeping the overall voltage the same. It is represented in Figure 6.

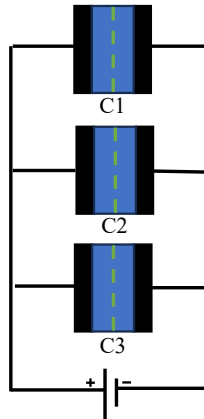


Figure 6: Supercapacitors in parallel connection.

The total capacitance and voltage of the parallel-connected supercapacitor cells are:

$$C_{total} = C_1 + C_2 + \dots + C_n \quad (9)$$

$$V_{total} = V_1 = V_2 = \dots = V_n \quad (10)$$

Similarly, if the parameters (voltage, capacitance) of the individual supercapacitor cell are the same, then the voltage and capacitance become:

$$C_{total} = n \times C \quad (11)$$

$$V_{total} = V \quad (12)$$

1.7 Supercapacitor Specification

Understanding supercapacitor cell and module parameters is important for different applications. To understand the key parameters and datasheet of a supercapacitor cell and module, the Skeleton Technologies supercapacitor single cell (SCA3200) [5], and module (skelmod-102V) [6], are selected as an example. The key parameters for the selection of the supercapacitor cell and module are explained in Table 1.

Table 1: Key parameters explanation of supercapacitor cell and module in a datasheet

Parameter	Value (SCA3200)	Value (Skelmod-102V)	Explanation
Nominal Voltage	2.85 V	102 V	The maximum voltage must match the required system voltage. It defines the normal operating voltage of the device and is used by the designer to ensure compatibility with the target system voltage level.
Absolute maximum voltage	N/A	108 V	This is the maximum charged voltage, if the voltage exceeds this value, there is a risk of damage. It specifies the upper voltage limit that must never be exceeded in operation or charging to avoid irreversible degradation or failure.
Rated Capacitance	3200 F	88 F	Maximum capacity of energy storage. It indicates the effective charge storage capability and is used to determine available energy and voltage sag under load.
Rated DC 10ms ESR	0.14 mΩ	6.2 mΩ	Internal resistance for 10-millisecond transient charge/discharge, which affects energy transfer due to voltage drop. Characterises internal resistance during short transient events and is critical for estimating instantaneous voltage drop and peak power capability.
Rated DC 1s ESR	0.18 mΩ	7.6 mΩ	Internal resistance for a 1-second transient charge/discharge, which affects energy transfer due to voltage drop. It represents internal resistance over longer transients and is used to assess losses, thermal stress, and sustained power delivery.
Specific energy	6.8 Wh/kg	4.8 Wh/kg	The ability to store energy per unit weight. The higher values mean a lighter system. It quantifies energy stored per unit mass and guides designers in evaluating weight constraints for mobile or space limited applications.
Energy density	N/A	4.3 Wh/L	The ability to store energy per unit volume. The higher values mean a small volume system. It describes energy stored per unit volume and is used to assess packaging efficiency and enclosure sizing.

Continue in the next page.

Table 1 continues

Parameter	Value (SCA3200)	Value (Skelmod-102V)	Explanation
Maximum stored energy	N/A	127.1 Wh	Check the total energy storage that is suitable for the application requirement. It defines the total usable energy at rated voltage and is used to verify suitability for system level energy buffering requirements.
Rated maximum peak current for 1 second	2.89 kA	2.69 kA	It is the highest current allowed for 1 second. It specifies the allowable short term current capability and is essential for ensuring safe operation during high power transients.
Maximum temperature	-40 °C	-20 °C	This is the maximum operating temperature range. It defines the upper operating temperature limit beyond which performance degradation or accelerated ageing may occur.
Minimum temperature	+65 °C	+60 °C	This is the minimum operating temperature range. It defines the lower operating temperature limit and is used to assess suitability for cold start and low temperature environments.
Projected cycle life @ RT, between VR and VR / 2	1,000,000 Cycles	1,000,000 Cycles	This is the estimated life cycle at an operating range of temperature and keeping the voltage between half of the nominal voltage to the nominal voltage. It indicates expected lifetime under specified voltage and temperature ranges and is used to evaluate long term reliability.
Nominal auxiliary supply voltage	N/A	24 V	Required nominal supply voltage for the operation of power electronics circuits. It specifies the required supply voltage for internal monitoring and protection electronics and must be provided by the system.
Auxiliary supply voltage range	N/A	16-33 V	Required range of supply voltage for the operation of power electronics circuits. It defines allowable variation in auxiliary supply to ensure correct operation of embedded control and protection circuits.
Maximum series voltage	N/A	1250 VDC	Only applicable when connecting several modules in series. The maximum number of modules that can be connected in series that the voltage does not exceed this value. Sets the maximum permissible voltage when modules are connected in series and is used to determine the allowable number of series connected units.

2 SCES: Installation and Maintenance

This section provides detailed instructions for the installation and maintenance of the Supercapacitor Energy Storage System (SESS) installed on marine vessels. The SESS is a critical component of the vessel's energy management system, and regular maintenance is essential to ensure its safe and efficient operation. This manual is intended for technicians, crew members, and system operators involved in the maintenance and operation of the SESS.

2.1 Safety Precautions

Before performing any maintenance and installation tasks, ensure the following safety precautions are observed:

- **Personal Protective Equipment (PPE):** Always wear appropriate PPE, including insulated gloves, safety goggles, and protective clothing.
- **System Shutdown:** Ensure the SESS is properly shut down and disconnected from the power supply before performing any maintenance and installation tasks.
- **Ventilation:** Ensure the compartment housing the SESS is well-ventilated to prevent the accumulation of harmful gases or vapours.
- **Fire Safety:** Keep fire extinguishers and other firefighting equipment readily available. Ensure that the fire detection and suppression systems are operational. N.B, in case of fire involving supercapacitor modules, CO₂ or dry powder extinguishers are recommended. Water-based extinguishers shall not be used on energised systems due to electrical hazards.
- **Training:** Only trained and authorised personnel should perform maintenance and installation tasks on the SESS.

WARNING 1: Failure to follow these instructions can cause a hazard at the customer site, be fatal for the user and damage the equipment.

WARNING 2: Hazardous mains voltage and/or capacitor voltage are present behind the protective cover. The components that can only be accessed by opening the protective cover with tools must not be operated by the user. Only qualified service personnel are authorised to remove such covers.

2.2 Installation of Supercapacitor Module

The supercapacitor modules are high-power devices that must follow a proper installation procedure to ensure safety and prevent hazards.

2.2.1 Module Handling

- Store in a dry and clean place and maintain its storage temperature according to the manufacturer's datasheet. i.e. -40 to +50 °C for Skelton module.
- Ensure proper PPE and ensure to never touch its terminals.
- Handle with care and tighten up with straps or use pallets.
- Lift the module with a Hydraulic Lift Table or a Manual Hydraulic Stacker.
- Rack installation
 - Use a rack that provides mechanical support, vibration isolation, and ensures sufficient airflow for cooling.
 - Use a proper size of mounting bolt with appropriate torque to tighten up.
 - The mounting surface and module must be levelled to handle the module's weight.

2.2.2 Power Cables Connections

- Use flexible and standard cables
- Cable selection must be based on system power requirements. Consider maximum voltage, maximum current and maximum temperature of the system during operation.
- Identify positive and negative terminals to connect the cable with the correct polarity.
- Use ring terminals or cable lugs with a proper crimping tool according to cable size.
- Use strain-released clamps to reduce weight on terminals.

2.2.3 Protection and Grounding

- Install a pre-charge circuit to prevent inrush current.
- Use fuses, contactors and circuit breakers for short circuit protection.
- Connect the rack or module to the earth ground.

2.3 Maintenance Tasks for Technicians

Technicians are responsible for the detailed inspection, testing, and repair of the SESS. The following tasks should be performed annually:

2.3.1 Visual Inspection

- Inspect the SESS cabinets for any signs of physical damage, corrosion, or wear.

- Check all electrical connections for tightness and signs of overheating.
- Inspect the ventilation system to ensure it is functioning correctly and that there are no blockages.

2.3.2 Electrical System Check

- Test the insulation resistance of the SESS components.
- Verify the integrity of the grounding system.
- **AUX Signals to Enclosure Isolation Resistance Check:** Use an insulation resistance tester to check the isolation resistance between AUX signals and the enclosure. Ensure the resistance is above 20 MΩ.
- **AUX Signals to Power Terminals Isolation Resistance Check:** Check the isolation resistance between AUX signals and power terminals. Ensure the resistance is above 20 MΩ.
- **Power Terminals to Enclosure Isolation Resistance Check:** Verify the isolation resistance between power terminals and the enclosure. Ensure the resistance is above 20 MΩ.
- Check the condition of the cables and connectors for any signs of wear or damage.

2.3.3 Cooling System Maintenance

- Inspect the cooling fan for any signs of wear or damage.
- Ensure the fan blades are clean and free from obstructions.
- Check the fan's rotation and ensure it operates smoothly.
- Verify that the cooling fan control wiring is secure and undamaged.

2.3.4 Supercapacitor Module Inspection

- Inspect the supercapacitor modules for any signs of swelling, leakage, or damage.
- Measure the capacitance and equivalent series resistance (ESR) of each module to ensure they are within the specified range.

2.3.5 System Calibration

- Calibrate the voltage and current sensors to ensure accurate readings.
- Verify the operation of the Power Management System (PMS) and ensure it is communicating correctly with the SESS.

2.3.6 Torque Check on Power Connections

- Use a torque wrench to check the torque on all power connections. Check for the appropriate torque value of the busbar, which has been mentioned in the commissioning manual. i.e. the recommended torque for the Skeleton busbars is 50 Nm.
- Retighten any connections that do not meet the specified torque.

2.3.7 Testing and Corrective Maintenance Tasks

Testing and corrective actions need to be performed according to the following problems mentioned in Table 2.

Table 2: Testing and corrective measures of the problems

Testing	Problem	Action Required
Measure the ESR of the supercapacitor module and compare it with its ESR value of EoL	ESR over end-of-life (EoL) condition	Module replacement
Measure the capacitance of the supercapacitor module and compare it with its capacitance value of EoL	Capacitance below end-of-life (EoL) condition	Module replacement
Check the connection between both terminals of the supercapacitor module	Open circuit between the module terminal	Module replacement
Measure the supercapacitor module temperature during operation	The module temperature rises faster than that specified in its maintenance manual	<ul style="list-style-type: none"> • Clean if the any contamination • Check cooling fans are working • Check for airflow closer • Measure the ESR of the supercapacitor module and compare it with its ESR value of EoL
Check receiving the CAN messages, if a module is equipped with CAN	CAN communication shutdown	<ul style="list-style-type: none"> • Reset the auxiliary power supply for 30 – 60 seconds • Check that auxiliary power consumption is within the specified range mentioned in its maintenance manual • Check CAN connections are properly connected • Change the CAN interface • Check the CAN bus rate • Replace the module if all checks pass and the problem still exists
Check for the protection cover against physical damage or contamination	Physical damage or contamination	Replace the protection cover

2.3.8 Module Replacement

If the capacitor module has severe visible damage like fire or electrical arcing outcomes, leaked chemicals (electrolyte) or other major damages (like case opening, broken or melted DC busbars or terminals etc.), contact a Skeleton Technologies representative and special instructions should be handled by the corresponding Environmental, Health and Safety specialist.

- **Preparation:** Disconnect the system from the DC link and discharge the module to below 0.5V. Carefully follow the discharge procedure according to the manufacturer's maintenance manual.
- **Replacement:** Remove the damaged module and replace it with a new one. Ensure the new module has the same rated voltage as other modules in the system.
- **Reconnection:** Reconnect the module and ensure all connections are secure. Charge the system to the rated voltage after replacement. Carefully follow the charge procedure mentioned in the manufacturer's maintenance manual.

2.3.9 Fuse and Contactor Replacement

- **Fuse/Switchgear Replacement:** Replace any blown fuses/switchgear with the correct type and rating. Refer to the switchgear specifications for the appropriate fuse/switchgear type. Use the Switchgear Installation and Mechanical Installation in the manufacturer's maintenance manual.
- **Contactor Replacement:** Replace any faulty contactors. Ensure the new contactors are of the same type and rating as the original. Use the Switchgear Installation and Mechanical Installation in the manufacturer's maintenance manual.

2.3.10 Emergency Discharge

- **Preparation:** Disconnect the system from the DC link and ensure the system is discharged to below 0.5V. Follow the step-by-step procedure from the SESS manufacturer's handbook/maintenance manual.
- **Discharge Process:** Use a discharge resistor to safely discharge the system. Monitor the voltage and ensure it remains below 0.5V. Follow the step-by-step procedure from the SESS manufacturer's handbook/maintenance manual.
- **Safety Jumper:** Place a safety jumper between the DC+ and DC- terminals to prevent voltage recovery. Follow the step-by-step procedure from the SESS manufacturer's handbook/maintenance manual.

2.3.11 Fault Diagnosis and Resolution

- **Diagnosis:** Use the master controller to diagnose any faults. Refer to the error logs and CAN messages for detailed fault information.
- **Resolution:** Address the underlying cause of the fault. This may involve replacing faulty components, adjusting settings, or resetting the system.

2.3.12 Predictive Maintenance Tasks

If, during routine maintenance, inspection or other works related to the system, it is determined that one or more parts of the system have visible or measurable damage or fatigue, report and schedule predictive repair or maintenance to mitigate the risk of unexpected system failure.

2.3.13 System Performance Monitoring

- **Data Collection:** Use the master controller to collect data on system performance, including voltage, current, temperature, and state of charge (SoC).
- **Analysis:** Analyse the collected data to identify any trends or anomalies that may indicate potential issues.
- **Action:** Take corrective action based on the analysis to prevent future issues.

2.3.14 Component Lifecycle Management

- **Component Inspection:** Inspect key components such as fuses, contactors, and cooling fans for signs of wear or fatigue.
- **Replacement Planning and review:** Plan for the replacement of components that are nearing the end of their projected lifecycle.

2.4 Maintenance Tasks for Crew

Crew members are responsible for routine checks and basic maintenance tasks to ensure the SESS operates smoothly. The following tasks should be performed regularly:

2.4.1 Daily Checks

- Check the SESS status indicators to ensure the system is operating normally.
- Monitor the temperature and humidity levels in the compartment housing the SESS.

2.4.2 Weekly Checks

- Inspect the SESS cabinets for any visible signs of damage or corrosion.
- Ensure the ventilation system is functioning correctly and that there are no obstructions.

2.4.3 Monthly Checks

- Verify that the fire detection and suppression systems are operational.
- Check the condition of the cables and connectors for any signs of wear or damage.

2.5 Maintenance Tasks for System Operators

System operators are responsible for monitoring the SESS and ensuring it operates within the specified parameters. The following tasks should be performed regularly:

2.5.1 System Monitoring

- Monitor the SESS performance data, including voltage, current, and temperature.
- Ensure the SESS is operating within the specified limits and that there are no abnormal conditions.

2.5.2 Alarm Response

- Respond promptly to any alarms or warnings generated by the SESS.
- Investigate the cause of the alarm and take appropriate action to resolve the issue.

2.5.3 Data Logging

- Maintain a log of all SESS performance data, including any alarms or warnings.
- Report any abnormal conditions or performance issues to the maintenance team.

2.6 Inspection and Testing Procedures

The following procedures should be followed during the annual inspection and testing of the SESS:

2.6.1 Insulation Resistance Test

- Use a Megohm-meter to measure the insulation resistance of the SESS components.
- Ensure the insulation resistance is within the specified range.

2.6.2 Capacitance and ESR Measurement

- To measure supercapacitor capacitance C , use the constant current charge/discharge method by applying a known current (I) for a time (t) and measuring voltage change (ΔV), then using $C = I \times t / \Delta V$.
- Replace any modules that are outside the specified range.

2.6.3 System Performance Test

- Perform a full system test to verify the SESS is operating correctly.
- Check the response of the SESS to different load conditions and ensure it is functioning as expected.

2.7 Troubleshooting and Emergency Procedures

In the event of a fault or emergency, follow these procedures:

2.7.1 System Shutdown

- In case of an emergency, immediately shut down the SESS using the emergency shutdown system.
- Ensure the system is isolated from the power supply before performing any troubleshooting.
- **Preparation:** Disconnect the system from the DC link and ensure the system is discharged to below 0.5V.
- **Discharge Process:** Use a discharge resistor to safely discharge the system. Monitor the voltage and ensure it remains below 0.5V.
- **Safety Jumper:** Place a safety jumper between the DC+ and DC- terminals to prevent voltage recovery.

2.7.2 Fire Emergency

- In the event of a fire, activate the fire suppression system and evacuate the area.
- Notify the crew and follow the vessel's emergency procedures.

2.7.3 Fault Diagnosis

- Use the system diagnostics to identify the cause of the fault.
- Refer to the troubleshooting guide in the manufacturer's maintenance/Integrator Manual for detailed instructions.
- **Diagnosis:** Use the master controller to diagnose any faults. Refer to the error logs and CAN messages for detailed fault information.
- **Resolution:** Address the underlying cause of the fault. This may involve replacing faulty components, adjusting settings, or resetting the system.

2.8 Record Keeping and Reporting

Maintain detailed records of all maintenance activities, inspections, and tests performed on the SESS. The following information should be recorded:

- Date and time of the maintenance activity.
- Details of the tasks performed.
- Any issues or faults identified, and the actions taken to resolve them.
- Results of any tests or measurements performed.

In the future, it will be considered for maintenance and diagnosis.

Regular maintenance of the Supercapacitor Energy Storage System (SESS) is essential to ensure its safe and efficient operation. By following the procedures outlined in this manual, technicians, crew members, and system operators can help to maintain the reliability and performance of the SESS, ensuring the continued safe operation of the vessel.

3 Fundamentals of Superconducting Magnetic Energy Storage (SMES)

3.1 Why SMES?

Popular electrical and electrochemical energy storage systems (EEES) include Superconducting Magnetic Energy Storage (SMES), Supercapacitor Energy Storage (SCES), and Battery Energy Storage (BES) systems [7, 8]. While each technology has its distinct advantages, this section focuses on the fundamentals of SMES, covering its working principles, key components, energy conversion mechanisms, and operational characteristics. The discussion extends to its unique advantages and typical applications. Comparative metrics such as energy density, power density, and round-trip efficiency are also summarised alongside other EEES technologies (i.e., SCES and BES).

SMES system is an energy storage technology that stores electricity in the form of magnetic field energy within a superconducting coil. A superconducting coil is a wire loop made of superconducting material (e.g., niobium-titanium, NbTi) that conducts electricity with zero resistance when cooled below its critical temperature. Therefore, a superconductor is a material that, when cooled below its critical temperature, exhibits zero electrical resistance. The zero resistance allows it to carry extremely high currents without significant energy loss, creating a powerful magnetic field to store energy. Unlike batteries or supercapacitors, SMES systems achieve near-zero energy loss during storage and release, making them ideal for high-power, short-duration applications [9].

SMES systems are uniquely suited for applications requiring rapid, high-power energy exchange because they store energy directly in the magnetic field of a superconducting coil, bypassing the inefficiencies of chemical (as in BES) or mechanical conversion (as in flywheels), enabling the following three distinctive performance characteristics [9]:

- Ultra-high efficiency due to zero resistive losses in superconductors; round-trip is reported as being between 80 – 97%.
- Instantaneous response (1 – 10 ms) for grid stabilisation (pulses of power) and power quality control.
- Long lifecycle (20 – 30 years) with minimal degradation, unlike electrochemical storage.

3.1.1 Comparison with Other Technologies

Energy storage systems can be broadly classified into five main types: electrical energy storage systems (EES), electrochemical energy storage systems (ECESS), chemical energy storage systems, mechanical energy storage systems and thermal energy storage systems. Each category is further subdivided into specific technologies.

ESS vary significantly in their performance, making them suitable for different applications. The most popular and efficient ESS are EESS and ECESS, shown in Figure 7. SMES, SCES, and BES are compared in Table 3 based on some selected characteristics [1, 8-13].

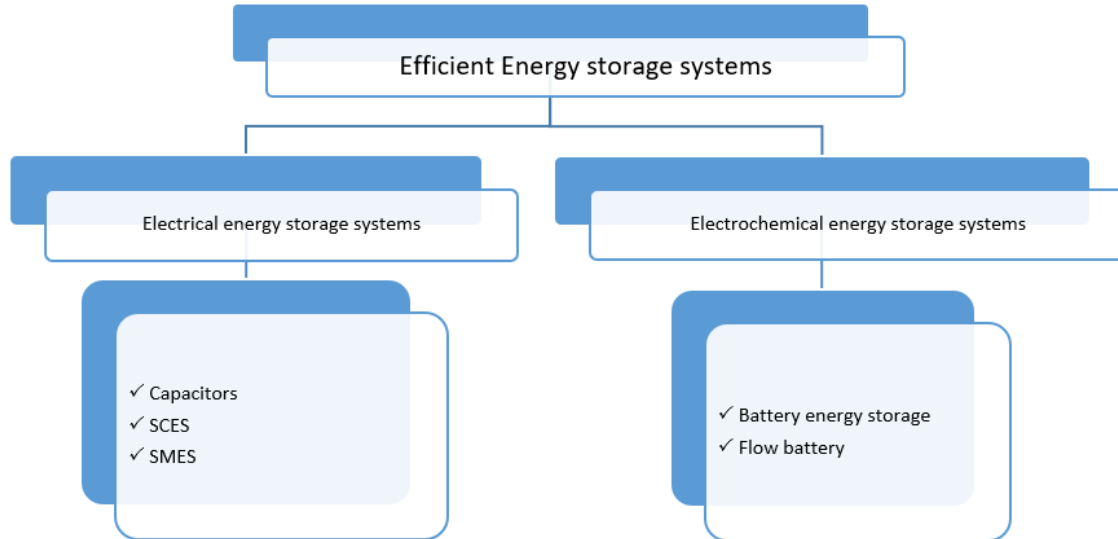


Figure 7: Electrical and electrochemical energy storage classifications.

Table 3: Comparison of SMES, SCES and BES.

S/No.	Criteria	Units	SMES	SCES	BES
1.	Energy cost	\$/kWh	1,000–10,000	300–20,000	140–780
2.	Energy	kWh	1–10	1–5	<10,000
3.	Power density	W/kg	10,000–100,000	1–10,000	150–1000
4.	Energy density	Wh/kg	0.5–5	5–10	30–270
5.	Round-trip efficiency	%	80–97	75–95	70–90
6.	Lifecycle	Years	20–30+	10–20	5–15

3.2 Basic Principles of SMES

3.2.1 Superconductivity

Superconductivity is a state of certain materials, when cooled below a critical temperature, that can conduct electricity with zero energy loss and the expulsion of magnetic fields. In this state, electrons move through

the material without any resistance, and the material expels magnetic fields (called the Meissner effect). Key features include:

- Zero Resistance: No heat/energy loss during current flow.
- Critical Temperature: Requires cooling (e.g., liquid or gaseous helium).
- Persistent Currents: No degradation over time (unlike batteries).
- High Current Carrying Capacity: Compared to conventional conductors, superconductors can carry 1000 times much, which makes them ideal for use in high-energy applications.

Some selected materials which exhibit superconductivity are presented in Table 4 [14]:

Table 4: Some selected superconducting materials and their properties

S/No.	Symbol/Abbreviation	Common names	Chemical formula	Critical temperature (K)	Critical magnetic fields (T)
1.		Lead	Pb	7.2	
2.		Niobium	Nb	9.2	
3.	NbTi	Niobium-Titanium alloys	NbTi	9.6	15
4.	Nb ₃ Sn	Niobium-Tin	Nb ₃ Sn	18.1	30
5.		Niobium-Germanium	Nb ₃ Ge	23.2	
6.	MgB ₂	Magnesium diboride	MgB ₂	39	14
7.	YBCO	Yttrium Barium Copper Oxide	YBa ₂ Cu ₃ O _{7-x}	90	100
8.	Bi2212	Bismuth Strontium Calcium Copper Oxide	Bi ₂ Sr ₂ CaCu ₂ O _{8+x}	80	100–150
9.	Bi2223	Bismuth Strontium Calcium Copper Oxide	Bi ₂ Sr ₂ CaCu ₂ O _{10+x}	125	50–100

3.2.2 Energy Storage Mechanism

SMES stores energy in the form of a magnetic field generated by direct current (DC) flowing through a superconducting coil. Unlike batteries (which store energy chemically) or capacitors (which store it electrostatically), SMES relies on electromagnetic energy storage, offering near-instantaneous energy release with minimal losses. The energy E_{SMES} stored in the magnetic field can be given as

$$E_{SMES} = \frac{1}{2}LI^2 \quad (13)$$

where L (Henry, H) is the inductance of the coil, and I (Amperes, A) is the current flowing through the coil. For example, A 2 H coil carrying 10 kA stores 100 MJ of energy and delivers $P_{SMES} = 20$ MW in $t_{SMES} = 5$ s based on (13) & (14) respectively.

$$P_{SMES} = \frac{E_{SMES}}{t_{SMES}} \quad (14)$$

3.2.3 Cryogenics

A superconducting coil is said to be cryogenically cooled when maintained at extremely low temperatures (typically below -253°C or 20 K) using liquid helium or nitrogen [15]. This cooling is important for the following reasons:

- The coil's material (e.g., NbTi) only exhibits zero electrical resistance at cryogenic temperatures.
- Without cryogenic cooling, the coil would lose its superconducting properties and behave like a normal wire, wasting energy as heat.

Superconductors can be classified into two categories based on critical temperatures and cooling requirements:

- Low-Temperature Superconductors (LTS) require extreme cooling, usually below 20 K (-253°C) and typically using liquid helium (~ 4.2 K). Common LTS materials include NbTi and niobium-tin (Nb_3Sn), widely used in wind turbine generators and high-field research magnets due to their stability under strong magnetic fields [15]. LTS systems demand rigorous thermal management to maintain liquid helium temperatures, often requiring multi-stage cryocoolers.
- High-Temperature Superconductors (HTS) operate at higher temperatures, usually above 20 K (up to 77 K with liquid nitrogen), reducing cooling costs. Examples include YBCO (yttrium barium copper oxide) or MgB_2 . HTS are being implemented in advanced applications like electric aircraft and naval propulsion systems [15]. HTS systems use simpler liquid nitrogen cooling but still require careful design to prevent thermal instability.

3.3 Components of an SMES System

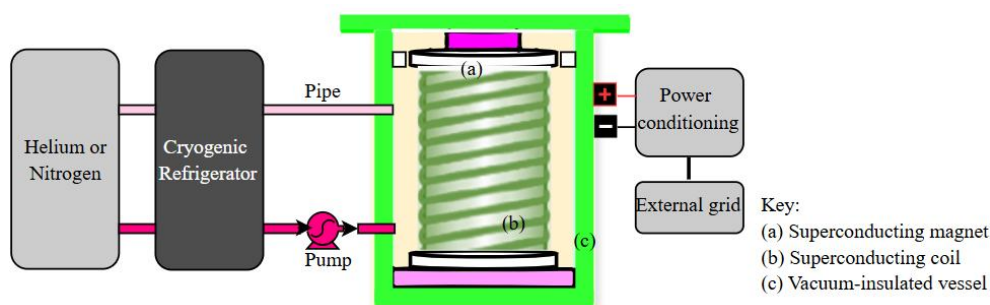


Figure 8: Schematic diagram of a superconducting magnetic storage system.

The schematic diagram of a typical SMES system is shown in Figure 8, comprising three major subsystems, namely: a superconducting coil unit, a power conditioning subsystem and a refrigeration and vacuum subsystem. The subsystems are broken down to the following: the superconducting coil, superconducting magnet, cryogenic system, power conditioning system, and control and protection system [7]. Each of these can be explained as follows:

3.3.1 Superconducting Coil: The core energy storage element

The superconducting coil is one of the most critical parts of an SMES system, where electrical energy is converted into magnetic field energy through the current flow. When energised, these coils carry extremely high currents without resistive losses, generating intense magnetic fields that store the system's energy. The energy stored is governed by (13). These coils are precision-wound from either LTS materials like NbTi or Nb₃Sn wires, or HTS tapes such as BSCCO, and MgB₂. The coil's geometric configuration significantly affects its performance. For example, solenoidal designs (Figure 8) are mechanically simple and can achieve high inductance values, but they generate substantial stray magnetic fields that require extensive active shielding. Whereas, a toroidal design, illustrated by Figure 10, inherently confines magnetic flux, minimising external field leakage, but introduces complex winding challenges and requires more complex structural support.

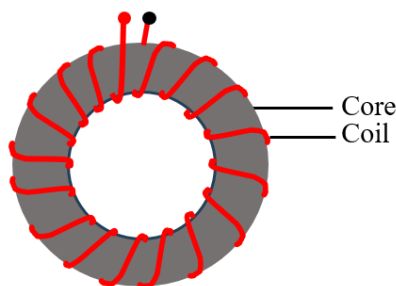


Figure 9: Toroid.

3.3.2 Cryogenic System: Maintaining the superconducting state

The cryogenic system (Figure 8) is responsible for maintaining the coil below its critical temperature. It is perhaps the most technically demanding subsystem with the power converter. The system maintains the coil at superconducting temperatures using liquid or Gas helium or by conduction through heat drains, incurring energy losses of approximately 2–3% for cooling operations. For LTS materials, this involves sophisticated and expensive liquid helium cooling systems operating at 4.2 K (-269°C). These systems must address three primary challenges: extreme thermal isolation, heat load management, and quench protection [8]. Modern cryostats employ multiple vacuum spaces with superinsulation (also called multi-layer insulation) comprising 10-30 layers of aluminised Mylar [16] to achieve heat fluxes below 0.1 W/m² below 20K [17].

Cooling is vital for SMES, with cryogenic cooling methods commonly used, including:

- I. *Liquid cryogen bath cooling method*: This can be categorised as:

- Liquid Helium (LHe): Liquid helium (4.2 K) serves as the primary coolant for many superconducting systems. However, its low latent heat of vaporisation makes it highly susceptible to evaporation from environmental heat ingress [18]. LHe is used for LTS (e.g., NbTi, Nb₃Sn) coils.
- Gaseous He.
- Liquid Nitrogen (LN₂): Liquid nitrogen (LN₂) cools HTS coils (e.g., YBCO) by maintaining them at its boiling point (77 K), where the latent heat absorbed during phase change removes thermal energy from the system. Lower cost and simpler handling than LHe, but limited operational magnetic fields [19]. It can be used as thermal shield to reduce the heat load at 20K.

Pros of the liquid cryogen bath cooling method:

- ✓ Passive, stable cooling via phase change.
- ✓ Proven in large-scale SMES.

Cons of liquid cryogen bath cooling method:

- Cryogen logistics (storage, refilling).
- Boil-off losses (up to 3% of stored energy/day).

II. Conduction (direct) cooling method

This method involves linking the coils thermally to a cryocooler (e.g., Gifford-McMahon, Pulse Tube) via solid conductive paths. It eliminates cryogens entirely. It is generally suitable for low-capacity applications, typically handling ≤ 10 W of heat load at 4.5 K to 100 W at 20 K operating temperature [20]. Other methods include forced-flow supercritical helium and hybrid cooling (LHe + cryocooler).

3.3.3 Power Conditioning System: Bridging DC storage to the AC grid

Power conditioning system (PCS) in ESSs comprises power electronics-based converters that perform energy conversion functions [21].

A complete PCS integrates [21]:

- Control systems for real-time operation management of ESSs
- Semiconductor switches (e.g., IGBTs, SiC MOSFETs)
- Passive components (transformers, inductors, capacitors)
- Thermal management systems (cooling for high-power operation)
- Safety devices for protection (overcurrent/voltage protection)
- Robust enclosures (EMI shielding and environmental protection)

The PCS enables seamless integration of diverse energy sources, each with distinct voltage characteristics. PCSs in ESSs are typically classified into two primary categories according to their output voltage characteristics at the interconnection point:

- DC bus-based PCS configurations, and
- AC bus-based PCS configurations.

Typical configurations are shown in Figure 2 in [21].

PCS interfaces the superconducting coil's DC operation (Figure 8). Modern SMES installations predominantly employ voltage-source converters using IGBT or SiC semiconductor devices. These systems must handle several unique requirements [21]:

- Bidirectional power flow capability (both charging and discharging)
- Ultra-fast response times for pulse of power
- High efficiency

3.3.4 Control and Protection: Ensuring system reliability

The control and protection systems are used in SMES installation in both routine operation and emergency response. Key functions include:

- Continuous monitoring of coil voltage (for quench detection)
- Active management of magnetic fringe fields
- Thermal monitoring of the cryogenic system

Quench protection is critical in SMES, as the abrupt transition from superconducting to normal state can release megajoules of stored energy within milliseconds, depending on coil self-inductance and current magnitude. A typical quench protection system with its dump (discharge) resistor is shown in Figure 1 in [22].

3.4 Working Phases

SMES operates through three synchronised energy conversion phases discussed briefly as follows [7]:

Charging phase: Current is ramped up in the superconducting coil. The magnetic field strength grows with current, storing energy according to (13).

Storage phase: The coil maintains persistent current with zero resistive loss. Cryogenic systems counteract heat leaks (0.1 W/m^2 for LHe-cooled NbTi).

Discharging phase: The stored DC current is transferred from the superconducting coil to the DC bus through a bidirectional power conversion system. Discharge duration depends on the self-inductance and the current flowing through the coil.

4 SMES: Installation and Maintenance

This manual is intended for technicians, crew members, and system operators involved in the maintenance and operation of the SMES.

4.1 Installation

Installing an SMES requires qualified and experienced operators. As there is no standard product, each company sends its own fitters to carry out installation, commissioning and important maintenance operations. It is recommended that the SMES is delivered in a pretested and preinstalled box or container from the supplier's premises. This 'container' can be considered a 'black box' for ship crews and owners. It protects the SMES equipment from dust and shock. The equipment is designed for maritime environments (i.e. salty atmospheres) to prevent corrosion. The inlet and outlet for electrical power and fluid management are designed to connect to the main power and auxiliaries onboard. The interfaces and connectors will comply with the requested standard. An air conditioning system is recommended to maintain the temperature inside the container and guarantee the performance of the SMES.

The SMES system in its container includes a superconducting coil in a cryostat, a cooling system (cold head or cryogenic fluid supply), and a control system or SCADA system to connect to the ship's main control system. If necessary, the SMES will be mounted in the container in an active or passive EM shield to mitigate the magnetic stray field, and on an adaptable, low-vibration platform to absorb ship vibrations and tilts.

As with any superconducting system, the cryogenic system will adhere to the local pressurised vessel standards and certification processes. This requires safety valves, a burst disc, etc., and the design must be approved by an authorised body. The SMES system will undergo testing prior to shipment for installation on board, in accordance with a testing programme defined and accepted.

If the SMES system fails, it will be disconnected in accordance with the given protocol. Repairs will be carried out during the ship's stopover.

During the installation phase the following actions must be carried out with the shipyard or the owner.

4.1.1 Electrical and Grid Connection

- I. Bus integration on board
- II. Verification of Grounding, fault detection,
- III. Coordination with external controllers (propulsion, grid, etc.)

4.1.2 Instrumentation and SCADA Integration

The SMES system has its own controller that checks the temperature, vacuum level and operation of the cryocooler. The level of detail required for data exchange must be defined with the shipyard. This can range from detailed life information, such as temperature versus time, to a

simple GO/NO GO alarm. According to the contractual requirements, the data can be stored for analysis: data loggers, alarms, telemetry connections

4.1.3 Commissioning and Functional Tests

- I. Vacuum level after commissioning
- II. Stepwise cooldown and temperature monitoring by the SMES supplier
- III. Full charge-discharge test under monitored conditions

4.2 Maintenance

This section outlines the basic preventive maintenance, inspection, developed under the V-ACCESS project. It specifically integrates risk mitigation recommendations derived from the V-ACCESS Risk Assessment. The SMES system components covered include the container that includes:

- MgB₂ superconducting coil and cryostat
- Cryocooler system
- Vacuum system
- Power conditioning system (PCS) / converter
- Protection resistance system
- Instrumentation (sensors, transmitters)
- Safety systems (alarms, shutdown systems)
- Cooling fluid circuits
- Structural support & enclosures
- Safety disconnection and emergency protocols documentation
- Maintenance planning

Table 5: General maintenance approach.

Task	Description
Visual inspection	Look for physical damage, corrosion, condensation, or unusual deformations.
Functional operation	Confirm operational performance by checking the alarm system
Alarm testing	Verify correct triggering and system responses.
Redundancy check	Confirm dual systems (like chillers) operate correctly.
Documentation	Log all maintenance steps, inspections, and findings.

4.2.1 SMES system

Maintenance tasks and steps:

- I. Visual inspection of the cryostat for any external damage or deformation.
- II. Structural inspection: inspect supports/suspension mechanisms for integrity.
- III. Maintenance operation of the cryocooling system cryostat seals every 10 years, or if leakage is detected by the supplier during a stopover in port.

Replacement steps:

- I. Helium flexible tubes every 10 years or upon damage.

4.2.2 Vacuum System

Replacement steps:

- I. Change the vacuum pump oil and service seals after the duration recommended by the pump supplier.

4.2.3 Power Conditioning System

Maintenance tasks and steps:

- I. Test turn-on/turn-off modes via HMI and GPIOs.
- II. Over/Under-current Verification
 - a. Supplier Testing: Detection systems validated during manufacturing or when the need arises (e.g., fault detection)
 - b. Onboard Operation: Power Management System receives alarms for crew notification and response
- III. Discharge resistor health and clean check: visual inspection

IV. Control logic firmware update check.

Replacement steps:

- I. Power electronics switches and CB contacts are inspected every 3-5 years.

4.2.4 Protection Resistance System

Maintenance tasks and steps:

- I. Visual inspection for dust or oil accumulation.
- II. Enclosure integrity check (stainless steel recommended).

Replacement steps:

- I. Clean and re-terminate connections during a stopover in port .

4.2.5 Structural & Mechanical Enclosure

Maintenance tasks and steps:

- I. Inspect for corrosion, structural cracks, or deformations.
- II. Verify fasteners are tight.

Replacement steps:

- III. Replace compromised mechanical supports – as soon as possible; the complexity will depend if this could be carried out onboard or otherwise.

4.2.6 Safety and Emergency Protocols

- I. Verify operation of emergency shutdown button and manual emergency power switches.
- II. Test gas detectors for oxygen monitoring.
- III. Inspect fire protection systems and confirm appropriate rating for electrical fires.
- IV. Test ventilation shutdown controls.

Additional Inspections for the fire and gas leakages include

- Fire risks due to dust/oil buildup require internal inspection of protection resistance.
- For helium release scenarios, verify ventilation and gas detection quarterly.
- Install warning labels for strong magnetic field zones to protect personnel with implants.

4.2.7 Spare and Redundancy Planning

Table 6: Other maintenance checklist summary.

Component	Action	Replacement Cycle
Vacuum System	Pump check, oil change	Oil every according to the recommended duration
Converter	Functional, safety check	Power electronics 5 years
Protection Resistance	Clean, inspect	Dust removal yearly
Safety Systems	Functional test	N/A

There are no available documents on the requirements on the use of SMES in the marine offshore industries at the time of writing this handbook. However, further the requirements on the use of supercapacitors in the marine offshore industries had been published by ABS [23].

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