Regulations in force and certifications

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Contents

1. INTRODUCTION TO SHORE-TO-SHIP POWER AND BATTERY UTILIZATION ON SHIPS

The global strategies for natural resources exploiting push towards reducing the environmental impact and improving the efficiency of the present and future energy solutions. In the maritime sector, major ship-owners and ports are beginning to consider the “green ship” concept, which can be declined into several technological aspects. From the owner viewpoint, high efficiency motors, electrical propulsion, variable speed drives, energy storage systems, low power light systems, new materials for hull construction and painting, etc. are among the solution under study. On the other hand, port operators and port authorities are considering electrical applications among the solutions for refitting or building of new port infrastructures (berths, piers, docks, etc.) in a more sustainable, but still profitable, way.

The marine sector moves almost the 90% of the total world shipped goods, and there are estimations which foresee to triple the present volumes of shipped goods, due to Asian markets rapid development [1].

When a ship is at berth, both at the pier or in the port bay, it utilizes onboard electric generators to supply shipboard technical and hotel services. For the time period the ship remains in the port area, she is responsible for relevant emissions of polluting agents as CO_2, NOx, SOx and particulate matter. For large city port areas, or when the port is within an environmentally restricted area, such emissions often can become the first source of air pollution [2].

The importance of the problem is reflected in international acts and regulations. In 2007 Californian Air Resource Board introduced “At-Berth Regulation” concerning emissions generated from the operation of auxiliary diesel engines on certain types of vessels whilst berthed at Californian ports [3]. Similar issues are included in EU directives: 2003/96/EC restructuring the EU Community framework for the taxation of energy products and electricity, 2005/33/EC as regards the sulfur content of marine fuels, 2006/339/EC on the promotion of shore-side electricity for use by ships at berth in EU Community ports and 2014/94/EC directive on the deployment of alternative fuels infrastructure.

In 2008, International Maritime Organization (IMO) tightened emission control rules defined in Annex VI of MARPOL convention, both for Sulphur content in marine fuel oil and NOx emissions from ship's diesel engines (Tier I-III norms) [4]. By 2020, maximum Sulphur content in ship's fuel must drop to 0.5% from current 4.5%. Effective from 2010, special rules which require the use of low Sulphur fuel are already applied to SOx Emission Control Areas (SECAs), where the target is 0.1% by 2015 [5]. Also, according to EU directive 2005/33/EC, from January 1st 2010 all inland waterway vessels and ships at berth in EU Community ports should use fuel with Sulphur content not exceeding 0.1 % by mass [6]. That means the ships in SECAs and Community ports will have to burn low Sulphur marine gas oil (MGO), or use alternative methods.

Considering more recent actions in this regard, the working group of the IMO dedicated to the greenhouse gas emissions rules agreed draft new mandatory measures to cut the carbon intensity of ships, building on current mandatory energy efficiency requirements to further reduce greenhouse gas emissions from shipping. The proposed amendments to the MARPOL convention would require ships to combine a technical and an operational approach to reduce their carbon intensity. The draft amendments were approved by the Marine Environment Protection Committee (MEPC 75), in November 2020, and have now been forwarded to MEPC 76 in June 2021 for adoption.

For the periods a large ship stays at the pier, a technique for locally eliminating emissions is the so-called “shore connection”. The technique foresees to switch-off the shipboard electrical generators for all the berthing period, and to provide electrical power for ship services from the land, using a dedicated cable line. Conventionally employed at Low Voltage (LV) levels, it has become available also for High Voltage (HV) systems (mainly voltages in the range 1 to 11 kV, and power exceeding 1 MW [7]), with the name of High Voltage Shore Connection (HVSC) (also referred as “cold-ironing” or “alternate marine power”) [8]. To make it convenient it is assumed that electric power is sold to owners at conveniently agreed prices, and also that the land-based production presents high efficiency and the largest employment of renewable sources. In this regard, there is an EU Commission Recommendation (2003/96/EG) that foresees the total or partial reduction of taxes on the electric power delivered to the ships using Shore Connections, thus making them more attractive for owners [9]. A shore connection is in fact an approach both technical and operational to the reduction of the greenhouse gases emissions, as foreseen by the IMO. In regards to the development of shore to ship power supply, a technical standardization effort is represented by the joint IEC (International Electrotechnical Commission), ISO (International Organization for Standardization) and IEEE (Institute of Electrical and Electronics Engineers) working group, which is working on the Std 80005 series. In particular, a standard for HVSC has been produced between 2008 and 2012 (the Std 80005-1 [10]), which has been then updated in 2019. Moreover, the Std 80005-2 [11] has been published in 2016, to define the data communication for monitoring and control to be used in shore connection systems for assuring interoperability among ship and shore sides. Finally, the Std 80005-3 is in draft at present, and it is aimed at defining the Low Voltage shore connection systems.

Conversely, onboard energy storage systems (usually batteries) have a long story. For a long time, they had only a support role in starting-power to emergency systems, safety equipment, communication and other less energy/power demanding solutions. However, the goal for the future is to use them for heavy duty onboard power requirement, such as propulsion and energy to diverse auxiliary systems throughout the ship operational profile. Indeed, modern battery technologies, coupled with the increasing electrification of onboard loads and the environmental protection regulations are pushing towards the use of onboard energy storage systems as a means of reducing onboard generators running hours, optimize their operation, or even to provide a zero-emission navigation mode (although for limited ranges). Ships using the hybrid power system concept (onboard conventional power generation plus batteries) are already sailing, and their number is increasing. Such a fast development of electric and hybrid-electric solutions for ships makes it relevant to focus on the regulatory context, for both regulations and standardization aspects. In this regard regulatory, standards, guidance and Class rules that address such topics are already present, but there are some aspects that are yet to be covered.

2. HIGH VOLTAGE SHORE CONNECTION

2.1 Introduction

A High Voltage Shore Connection (HVSC) is a shore connection system using either 6.6 or 11 kV cables to connect shore and ship. It is intended to deliver medium/high power levels (above 1 MW), to ships like RORO/Ferries, Container ships, Cruise ships, LNG/Tankers, and so on.

Exiting realizations already proof the technical feasibility of HVSC for almost all the types of ships of interest, regardless of different voltage or frequency levels between land and shipboard electrical power systems. The integration of such systems in all the ports is usually related to other obstacles. These typically are: limited port distribution system capacity (in both power and voltage levels); limited port supply line capacity (in both power and voltage levels); room availability to install HVSC dedicated cables, sockets, switchboards, converters and transformers; the need for upgrading shipboard Power Management System (PMS) to parallel the ship to the land grid and to avoid black-outs (especially for passenger ships). From ship's point of view, this means that in practice it is required to change so much things to make it better using a new ship designed with HVSC for these applications, rather than retrofitting a shore connection on an old ship (while it is possible to do the latter, and it has been done in the past, the required work is rather big and difficult to justify).

A relevant impact is certainly given for small ports or single pier stations, formerly fed in medium voltage (i.e.in the range 10 to 60 kV), to improve supply line voltage levels to HV ones (i.e. at voltages exceeding 100 kV). This brings problems of augmented earth fault currents, so that the port earthing system should be re-designed, along with the need of assuring additional multi-MW generating capacity from the land power system.

The high demands and complexity of issues connected with a supply of shore-side electricity to ships at berth has led to the elaboration (in cooperation with the IMO) of the European pre-standard IEC/PAS 60092-510:2009 Electrical installations in ships - Special features - High Voltage Shore Connection (HVSC) Systems, which describes the general requirements related to S2SP systems. On this basis the International Electrotechnical Commission has issued standard HVSC Systems - General requirements (the IEC/ISO/IEEE Std 80005-1) [10]. This standard describes HV shore distribution systems, shore connection and interface equipment, transformers/reactors, semiconductor/rotating convertors, ship distribution systems, control, monitoring, interlocking and Power Management Systems (PMS) of ships [12]. Power electronic converters (PECs) have been mentioned in the standard as a solution providing supply flexibility, covering both 50 Hz and 60 Hz mains frequency standards. However, the application of PECs might bring about supplementary merits, which are not described in the standards and subject matter literature.

2.1.1 State of the art

The possibility for ships at the pier to switch-off onboard generators is becoming more and more interesting for an increasing number of ship categories. Environmental restrictions, incentives, the maturation of standard practices and technical standards are factors that could give a rise to a more extended use of HVSC. Rules, incentive policies, maritime zones restrictions, and sustainability conditions to build new port areas or to refit disused port areas could be the key factors in developing HVSC systems. Less impact is observed from economic incentives on delivered energy or from other technical-economical motivations at the moment. HVSC systems appear to be successful whereas they become an "enabling" technology, rather than simply a "more convenient" technology (owners in particular seem not ready to assume economical risks on pure technological bases for this technology). The standard is at the moment the first technical reference and it briefly covers the following topics:

- the HV pier distribution system;
- the connection and interface (from shore to ship) devices;
- the HVSC dedicated port distribution transformers;
- the HVSC power converters (either rotating or static);
- the shipboard distribution system;
- the overall management system to parallel land and shipboard grids and control power fluxes.

The Standard 80005-1 does not apply neither to LVSC system, which are covered by Std 80005-3 still to be published, nor to the dry-dock recovering of the ships.

2.2 General Aspects of HVSC on cruise vessels

Reference is here made to cruise ships, since these are the most powerful users of HVSC systems. While other type of vessels would benefit/use HVSC (such as ferries), the use of cruise ships as an example allows to provide information that are valid for all the use cases, at the same time considering the worst case.

During stay at port, a large cruise vessel requires a power of about 8 to 12 MW to manage the various on-board services [13]. Such power is normally generated by one of the main diesel generators producing, in service, SOx, NOx, CO2 and particulate matter. The quantity of emission in eight hours (average) stopover at quay of a cruise ship is very high. A method of reducing such pollution is the connection of the Vessel to the HV shore grid, thus allowing the stopping of the auxiliary engines during port operation. Since 2001 the cruise companies started providing the cruise vessels with facilities for supplying the Ship from HV shore power.

2.2.1 High Voltage Shore Connection on Large All Electric Cruise Vessels

The typical electric Integrated Power System (IPS) of an all-electric cruise liner [13] is shown in Fig. 1. In this example five Diesel Generators (DG1, DG2, DG3, DG4 and DG5) and one Gas Turbine Generator (GTG) are installed and connected to two interconnected main switchboards (AFT MSWB and FWD MSWB).

The voltage level normally employed in the HVDC section of the IPS is 11 kV for larger or 6.6 kV for smaller vessels. Such voltage levels are required for electrical distribution, as onboard power station size can be higher than 65 MW in a large vessel. The main switchboard supplies the main users such as propulsion system, bow and stern thruster electric motors, air conditioning compressor electric motors, MV/LV transformers feeding engine room substations, accommodations services and galley.

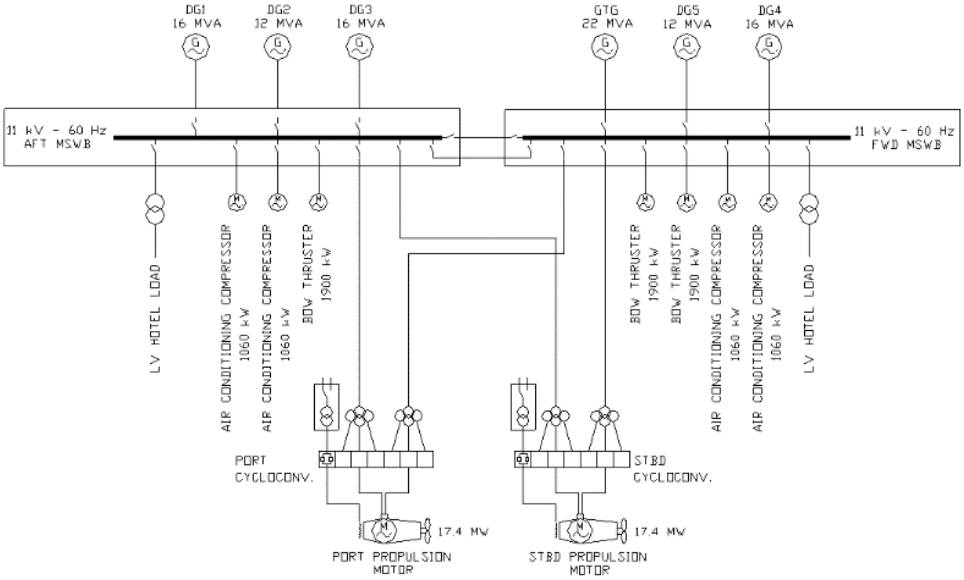


Fig. 1. Integrated Power System of an all-electric cruise liner [13].

The frequency of the generating system on a passenger vessel is typically 60 Hz. This allows an easy Shore Connection of vessel in countries where grid frequency is 60 Hz. In Europe or other countries, where grid frequency is 50 Hz, it is necessary to provide the shore side plant of additional devices for frequency conversion. Two solutions are normally proposed: static converters or rotating converters (Fig. 2). Considering that, as already indicated above, a modern all-electric cruise liner at pier normally needs 8 to 12 MW [13]. Thus, the frequency converters shall satisfy such power demand and at the same time shall provide enough short circuit current for correct intervention of electrical protection relays installed on ship electrical plant.

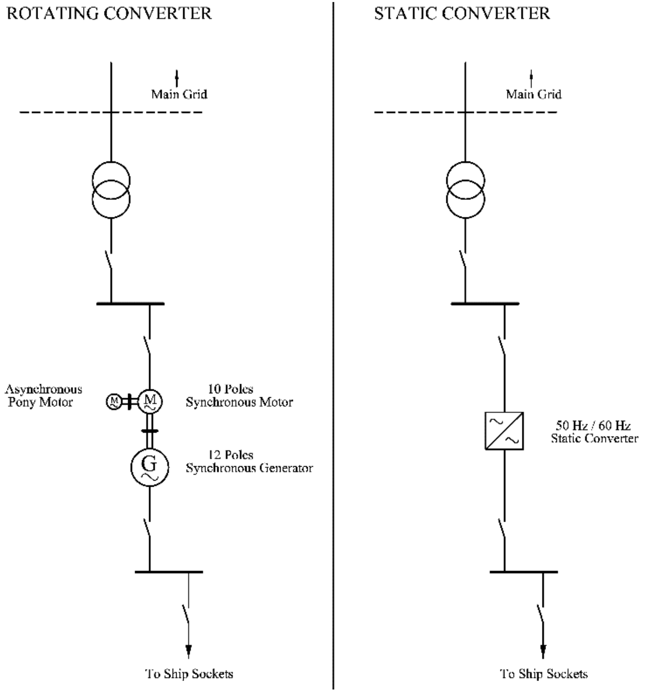


Fig. 2. The use of static or rotating converters [14].

Fig. 3. Typical switchboard for Shore Connection purpose [14].

For the physical connection of the ship to shore line, a dedicated HV switchboard power cubicle with special sockets is installed on board of the vessel [14]. The typical switchboard for Shore Connection purpose, with details of shore supply cables plug and socket connections, is represented in Fig. 3.

In Fig. 4 a simple block diagram of the typical ship side plant is sketched. It is composed by the following equipment:

- the Shore Connection cubicle breaker (CB "A"), installed in the High Voltage Shore Connection (HVSC) room;
- the MSWB Shore Connection circuit breaker (CB "B"), part MSWB;
- the HV cable interconnection link between CB "A" and CB "B";
- the Shore Connection control cabinet necessary to allow the communication between the ship and the shore side substation.

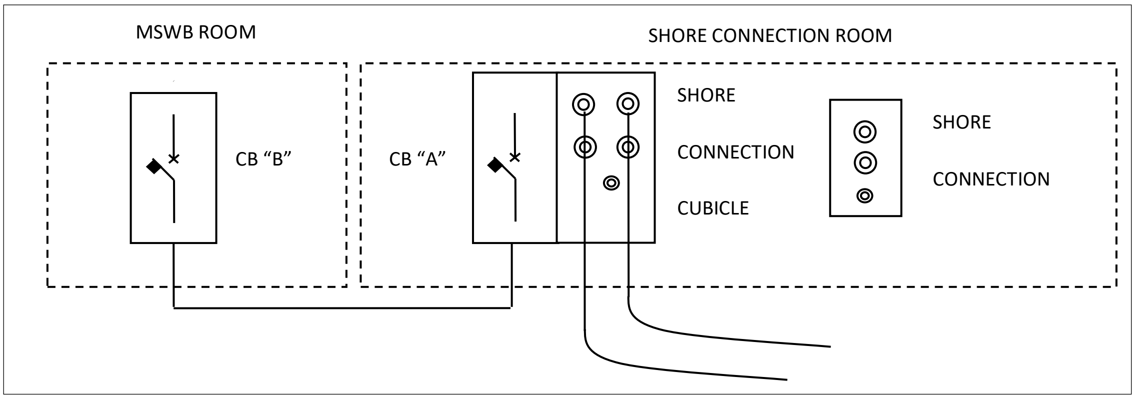


Fig. 4. Simple block diagram of the typical ship side plant [14].

Fig. 5. Shore Connection control cabinet [14].

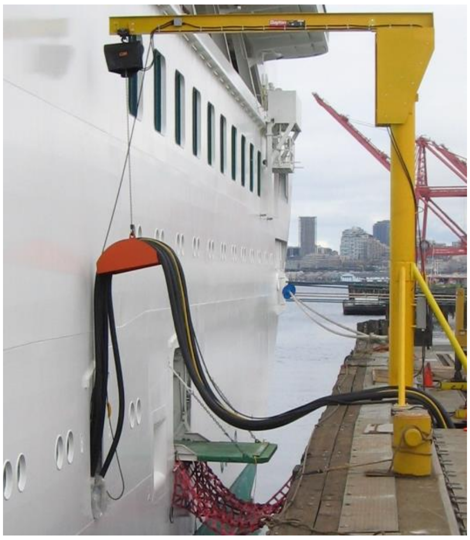
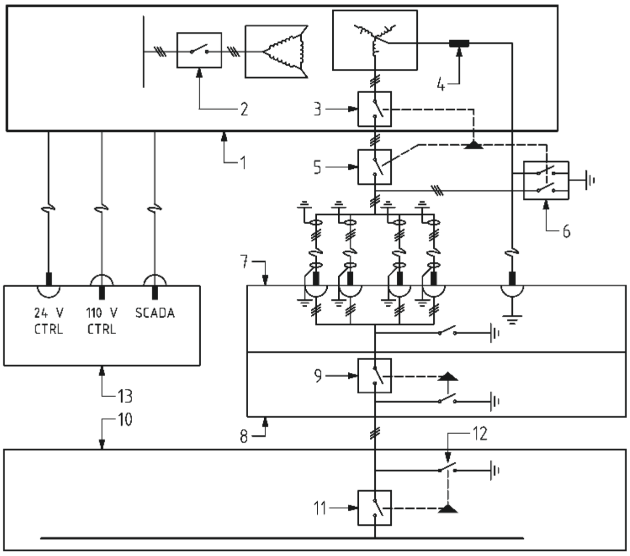


Fig. 6. Dedicated crane [14].

A Shore Connection control cabinet with relevant plug and socket connections for the Ship to Shore communication is shown in Fig. 5. When the ship is at pier, the cables and the plugs connecting the vessel to shore substation are managed by the quay operators that, through a dedicated crane, line up the cables to ship shell door. Fig. 6 gives an example of the arrangement described.

In Fig. 7 is shown the one-line diagram of the HV Shore Connection plant defined by the IEC/ISO/IEEE standard [10] in which the shore side distribution transformer star point is connected to ship hull through a neutral resistor with a dedicated neutral line. This arrangement is needed because on the cruise ship the star point of each generator is grounded to hull through a high resistance earthing resistor in order to limit the ground current in case of earth fault. During vessel shore operation the same protection principle is maintained. The IEC/ISO/IEEE standard requires also an equipotential bonding between the ship's hull and shore earthing electrode. The ground connection is to be continuously monitored by a dedicated permanent insulation monitoring device. In case of loss of the equipotential bonding, the ship Shore Connection is to be immediately shutdown and a restoration of power through the main diesel alternators is to be carried out.

The signals managed by the Shore Connection control cabinet (Fig. 5) are illustrated in Fig. 8, including the ground check monitor device alarms. Whereas Fig. 9 shows the details of the power and earth contacts on a power sockets installed on the HV Shore Connection cubicle.



KEY

1. SHORESIDE SUBSTATION
2. TRANSFORMER PRIMARY CIRCUIT BREAKER
3. TRANSFORMER SECONDARY CIRCUIT BREAKER
4. NEUTRAL GROUNDING RESISTOR
5. DOCK DISCONNECT SWITCH
6. DOCK GROUND SWITCH
7. SHIP'S SHORE CONNECTION CUBICLE
8. SHIP'S BREAKER CUBICLE
9. SHORE CONNECTION CIRCUIT BREAKER
10. SHIP'S RECEIVING SWITCHBOARD
11. RECEIVING CIRCUIT BREAKER
12. GROUND SWITCH
13. SHIP'S CONTROL CUBICLE

NOTE

a. DUAL SECONDARY 11 kV AND 6.6 kV TRANSFORMER MAY BE USED
b. 24 V CTRL IS 24 VOLTS DC, 110 V CTRL IS 110 VOLTS DC,
AND SCADA IS SUPERVISORY CONTROL AND DATA ACQUISITION

Fig. 7. One line diagram of the HV Shore Connection plant [10].

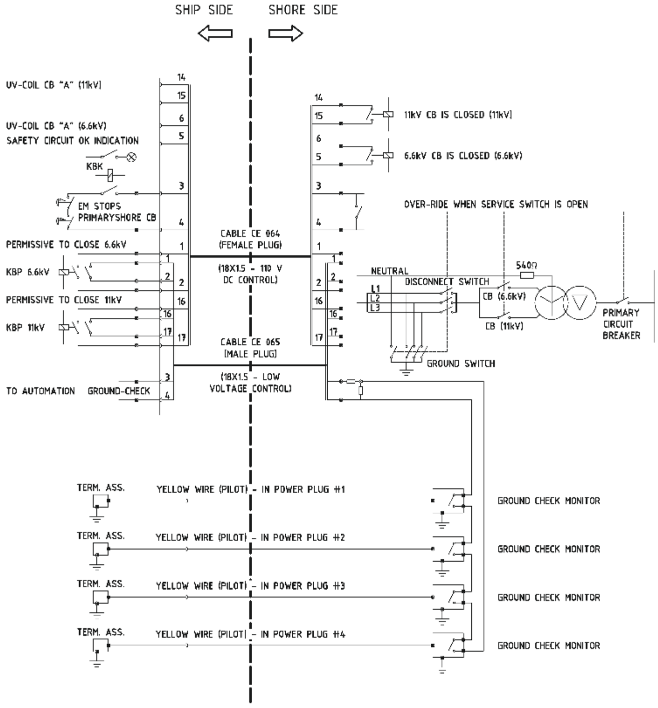


Fig. 8. Signals managed by the Shore Connection control cabinet [10].

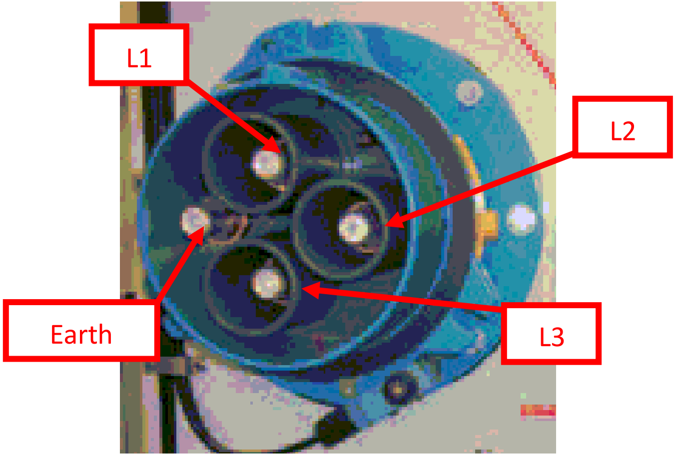


Fig. 9. The power and earth contacts on a power socket installed on the HV Shore Connection cubicle [14].

2.2.2 High Voltage Shore Connection Sequence on Large All Electric Cruise Vessel

After the ship is alongside the quay and physical connected to shore line, i.e. all power and signal sockets are correctly plugged in, the connection sequence can be carried out. The sequence is managed by the ship automation system. The operator can remotely control all the operation from a workstation located in Engine Control Room

(ECR), which is the space normally manned during various ship operation.

The sequence is actually carried out by the Power Management System (PMS) software i.e. by the part of ship automation system specifically dedicated to the control the generating system of the vessel including the starting/stopping and synchronization of generators. The PMS also gives to the operator all the feedback from the generating plant such as power available, frequency network, kW, kVAR, kVA etc. The shore connecting sequence is divided in two phases:

- shore side connection, energization and set up of the ship network;
- ship side closing sequence.

In the first phase, PMS checks all the interlocks and conditions that need to be satisfied in order to set up the ship to receive power from shore substation as follow:

- only one DG is to be connected to the ship network, (the ship transfer operation can be carried out with one DG only on the network);
- all circuit breakers are ready for operation;
- all pugs are correctly connected;
- no emergency stops are activated.

When the operator in ECR receives the information from the PMS that the first phase is conclude, the ship informs the shore side electrical substation that the vessel is ready to receive voltage from shore.

Once the shore substation transformer secondary circuit breaker is closed and shore gird voltage frequency and phase sequences are checked, the ship officer on duty can instigate the closing sequence (phase two) by a dedicated command on ECR workstation. After the PMS receives the starting sequence command, immediately the ship shore circuit breaker “A” is closed, and start the diesel generator synchronizing sequence. First the generator voltage is adapted to shore side voltage acting on alternator automatic voltage regulator and then the frequency phase angle is also adapted acting on diesel alternator speed regulator.

Once synchronizing is achieved, the circuit breaker “B” is closed and PMS starts the ship to shore load transfer sequence. The PMS, acting on the speed regulator and automatic voltage regulator, transfers the active and reactive power from ship to shore. When the power generated by the diesel generator reach a predetermined threshold, the relevant circuit breaker is opened and the vessel is now supplied from shore.

The sequence from shore to ship follows the same philosophy principle. In summary: first one diesel generator is started and synchronized and connected to the ship network supplied from shore, then the PMS manages the load transfer from shore to ship. At the end of the sequence, the shore circuit breakers are automatically opened. In case of Shore Connection shutdown, the PMS automatically performs an operation of power restoration through the main diesel alternators after the consequent blackout.

2.3 Shore to ship connection and ship’s infrastructure

The weakest link of HVSC is shore to ship connection equipment, particularly cable management system (CMS). A well-designed CMS should enable fast connection and disconnection of the shore supply and must be completely safe for personnel involved in connection procedure and harbor operations. It is very important to predict and compensate possible ship movements caused by tidal ranges and draft. It should also ensure that cables do not interfere with mooring and cargo handling operations.

There are two possibilities for placing the CMS: onboard ship or at a berth terminal (Fig. 10) [15].

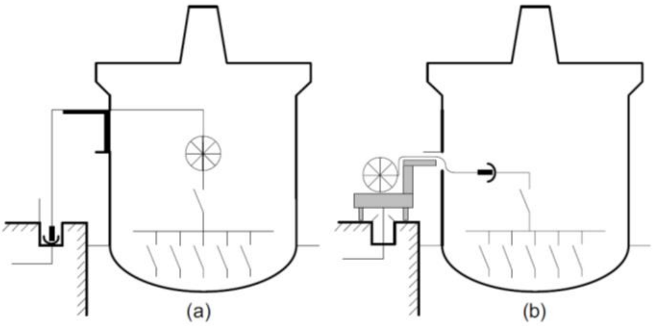


Fig. 10. HVSC with CMS placed onboard ship (a) and on shore (b) [15].

In case of onboard CMS placement (Fig. 10a), connection boxes with one or more sockets must be installed next to the berth. They should be located in separate, especially designed pits, capable of withstanding heavy wheel loads of harbor machinery. Ideally, there should be 3-4 connections per quay, to prevent usage of long cables which may be the obstacle for mooring lines.

If the CMS is placed on shore (Fig. 10b), the main part of ship’s infrastructure is the shore connection panel, consisting of the main circuit breaker, protection relays, grounding cable and proper control interface between shore side and ship’s integrated automation system. It must provide fully automated synchronization and load transfer between incoming shore power and ship’s generators. Like all HV switching equipment located onboard a ship, shore connection panel must be placed in a dedicated room with limited access to the designated personnel only [16].

Together with HV phase cores, power connecting cables must also contain communication line between the ship and shore side power supply. Indeed, the 80005-2 [11] standard requires the use of a fiber optic line embedded in the power cable between the shore and a ship, as shown in Fig. 11, coupled with a dedicated ICT infrastructure on both sides.

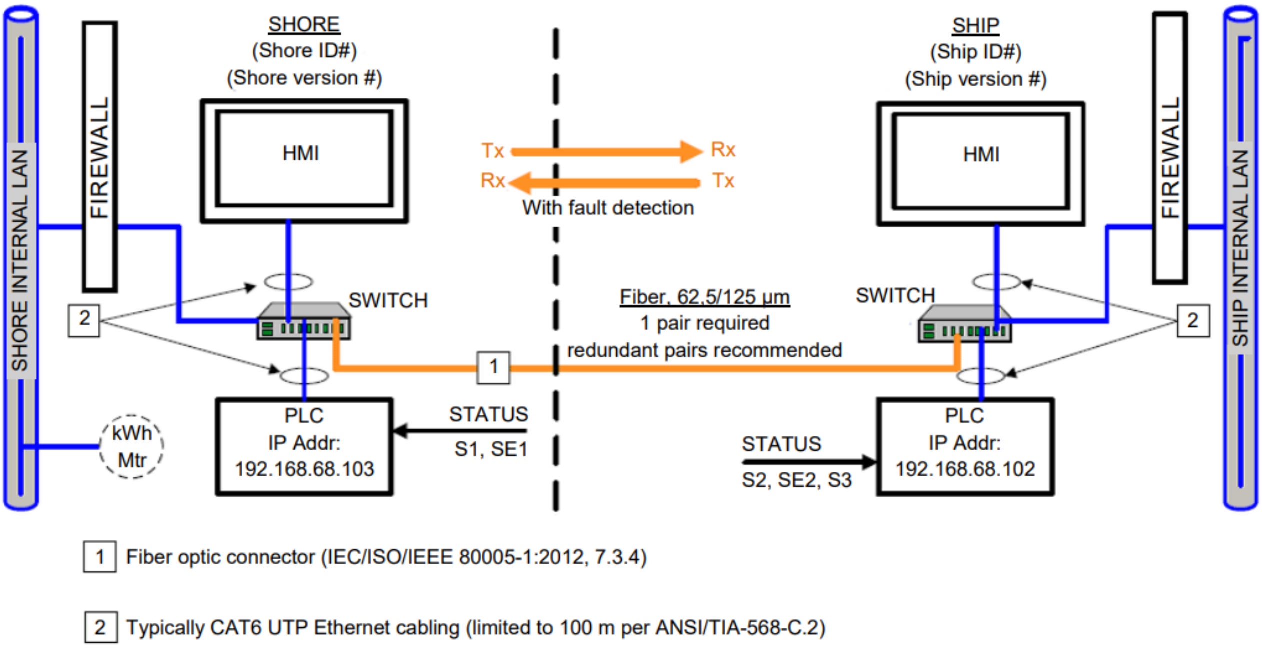


Fig. 11. Data communication general diagram [11]

While cruise ships can be directly supplied in HV, as previously depicted, the majority of cargo vessels currently in operation are using low voltage electrical power system (typically 400-690 V). Therefore, to receive 6.6 kV or 11 kV shore side power supply they need to be retrofitted with power transformers (Fig. 12).

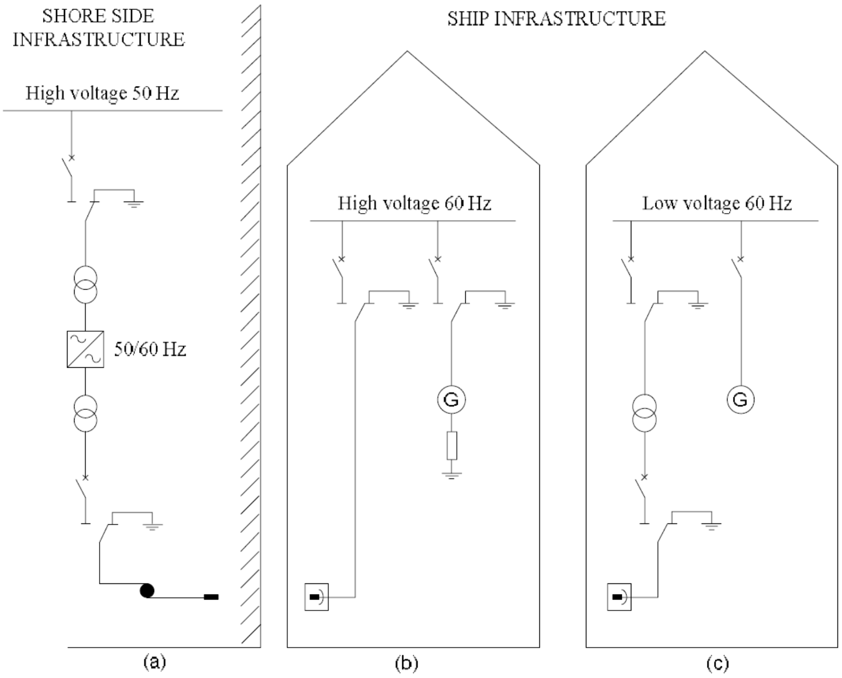


Fig. 12. Line diagram of HVSC system for shore side (a), ships with high voltage power system (b) and ships with low voltage power system (c) [15].

Although a lot of HVSC equipped ships are storing cables onboard, placing the CMS at the terminal is better solution. CMS platform located at the terminal can be movable, thus enabling supply at different points along the berthing terminal. Autonomous movable CMS can be supplied by cable in the same way as harbors cranes are. Pit sockets are much more sensitive to weather and moisture than the cable gland which can be placed in heating resting socket on much higher altitude from the sea. It is also easier to compensate tidal oscillations, draft changes and wind squall, especially when pivoting boom is used for cable feeding [15].

2.4 HV Shore connection electrical safety

A delicate topic is the one related to the system's protection. In fact, the safety of a 6.6/11 kV interconnection that is foreseen to be applied and removed once a day is particularly critical. Moreover, different ships use the same shore connection system throughout its life, highlighting the requirement of designing a system that is capable of working with a large selection of different ships, whose maintenance grade is not known. Therefore, the IEC/ISO/IEEE 80005-1 standard gives particular attention to the electrical safety topics.

2.4.1 Grounding requirements

The 80005-1 standard requires a TN-system with double ground connections.
On shore side, the neutral point of the transformer must be connected to the Ground Collector Bus bar via a resistor (R) (Figure 4). The ground collector has to be connected to the global shore grounding system to reduce the overall resistance of the global system. With regards the ship's hull, the standard mandates the connection to the grounding collector via a dedicated equipotential bonding conductor (PE) as shown in Fig. 13. These requirements are clearly stated in the section 6.2.4: "*equipment grounding conductors terminated at the shore power outlet box receptacles shall be connected to the ship and continued to the ship to create an equipotential bond between the shore and ship*". The ship itself has a common equipotential node (CEN), connected to the hull.
The equipotential bonding between the ship's hull (CEN) and the shore grounding system avoids any possible potential difference between the dock and hull, making the shore connection use safe both for port personnel and ship's guests (e.g. cruise ships). The rating of the grounding resistor R should be in accordance and coordinated with the ship's on-board system. The protection devices have to detect the minimum ground fault ($I_a(t_a) <= I_F$) that has to be significantly higher than the charging current of the equipment.
The standard in the article 6.2.3 prescribes the neutral grounding resistor rating in amperes, minimum 25 A continuous, shall not be less 1.25 times the preliminary system charging current.

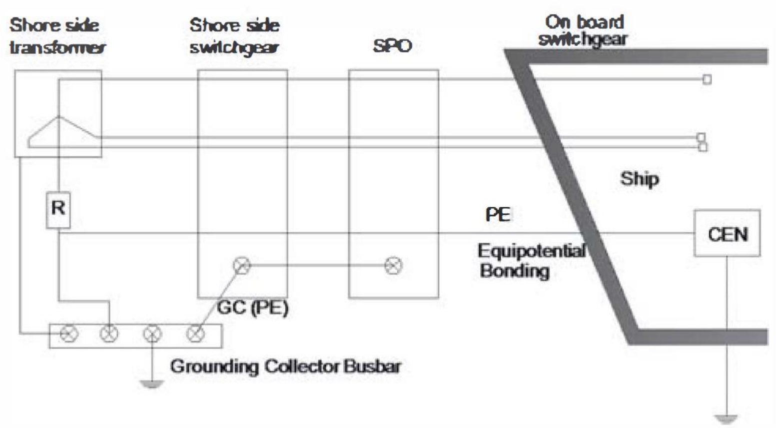


Fig. 13. Typical grounding system of HVSC as mandated by IECIISO/IEEE 80005-1 [17].

Since any kind of ship may be expected to dock at the berth, this resistor's value should be modified as needed by the type of ship expected at the berth. In particular, the standard prescribes the resistor R equal to:

- 335 Ω at Un =11 kV and 200 Ω at Un =6. 6 kV for cargo ships (Annex B),
- 540 Ω at Un =11 kV for cruise ships (Annex C),
- 200 Ω at Un =6. 6 kV for container ships (Annex D).

In the IEC approach, following a ground fault I_F in a part of the installation supplied by the U_o nominal a.c. line to ground voltage, a safe condition at any point of the installation is guaranteed, if the touch voltage persists not in excess of the maximum time t_a that guarantees U_t not higher than U_{Lt} (t_a) the permissible touch voltage:

$U_t = (Z_t/Z_s)\, U_o \leq U_{Lt}\, (t_a)$

$I_F = U_o/Z_s$

$I_a\, (t_a) <= I_F$

In the first equation, Z_t is the ground-fault conductor impedance depending on the type of system grounding and Z_s is the impedance of the complete ground-fault circuit (fault loop impedance). At this aim, a protective device with an operating current I_a ensuring the automatic disconnection in a tripping time t equal or lower than the value t_a.

In the shore-side transformer substation, (Fig. 13) for a ground fault in the primary section, the assigned tripping time t_a of its protective device defines U_{Lt} (t_a) and, knowing the I_F, it is possible to calculate the admissible Z_s and therefore the Z_t.

In HVSC, the hazard related to an electric shock is increased by the presence of seawater and the possible reduction of the human body overall resistance, especially at the interface area between the shore and the ship. In any case, the standard prescribes U_L equal to 30 V. "*An earth fault shall not create a step or touch voltage exceeding* $U_L = 30$ *V at any location in the shore to ship power system*" (article 6. 2.3).

In HVSC side, the Zs = R+ Zt + ZL is the impedance of the complete ground-fault circuit (fault loop impedance), R is the resistance of the neutral grounding resistor and the phase line impedance ZL is negligible.

In the case of TN- system double grounded (on the shore and on the ship) (Fig. 13), for a shipside fault, the Z_t is equal to the impedance Z_{PE} of the equipotential conductor in parallel to the series of the two ground resistances R_{GS} and R_{CEN}. These two resistances are:

- R_{GS} of the grounding system on the shore, that is known;
- R_{CEN} of common equipotential node on the ship (i.e., the hull), that is variable for each ship.

In other words, a shipside fault current circulates in the path with the lowest resistivity; since no other intentional connections are present, the PE conductor, grounded at the extremities on the shore (OS) and on board the ship (CEN), is the current path.

It is conservative to consider $Z_t = Z_{PE}$, a known and very low value and suitable to be independent on knowing the R_{CEN} dependent on each ship. Z_{PE} value is negligible in comparison to the R value. In any case, it has to be lower than

$Z_{PE} = 30\, R \,/\, (U_o - 30)$

In the case in which the equipotential bonding conductor PE is not adopted or it is broken, for a shipside fault, the system becomes a TT-system that is grounded independently on the shore and on the ship. The loop impedance is practically equal to $Z_s = R+R_{GS}+R_{CE}$ and the touch voltage impedance for a side ship fault is essentially equal to $Z_t = R_{CE}$. It has to be of value very low also if with arcing fault, to guarantee 30 V.

In IEC approach, this well-known condition makes preferable the TN-system, also double grounded (Fig. 13), that guarantees a $Z_s = R+Z_{PE}$ of known and controlled low value.

Since the continuity of the PE is fundamental to ensure these safety requirements, the bonding should be continuously monitored, shutting down the whole process if a loss of continuity is detected, The PE conductor represents the only intentional, thus reliable connection that can ensure the requirements listed at the point 6. 2. 3 of the IEC/ISO/IEEE 80005-1. Other connections, such as the docking ropes, are generally realized using synthetic non-conductive materials. Indeed, ships are usually docked via Nylon, Polypropylene or Polyolefin ropes that will not represent a low impedance loop (Fig. 14).

Fig. 14. Ship docked at the berth using nylon ropes [17].

The only reliable connection that can ensure the maximum limit of 30 V is then the considered PE conductor.

A loss of continuity of the equipotential bonding PE causes a change of the coordination parameters (from $Z_s = R+Z_{PE}$ to $Z_s = R+R_{GS}+R_{CEN}$) and may cause a potential difference; let alone may interdict the first fault revelation by the protection equipment. The worst-case scenario in fact, should consider that the cable shield could be damaged by an external/internal cause. Other non-intentional connections cannot be taken into account, because their resistances may vary widely. As a result, the fault current may be too small to be detected by the protection devices.

The PE connection double grounded (on the shore and on the ship) however may generate both corrosion problems and transferred potentials which can be solved (or at least mitigated), by applying the approaches depicted later below.

2.4.2 Protection systems requirements

The safety of an HV shore connection is not only attained by means of proper grounding, but also through the correct definition of the protection systems, as well as their proper coordination [18].

Coordination with on-board loads protections: The IEC 80005-1 requires that shore substation needs to provide enough short circuit current to trip the protection relay of the biggest load on the ship, in the case of short circuit on the ship side.

A particular attention has to be paid to ANSI 50/51 and 50/51N protections coordination requirement, considering limited level of short circuit currents provided by static frequency converters and that shore protection system need to be set according to each ship.

Output transformer protection: Dedicated attentions have to be paid for shore system internal faults. Transformer internal faults such as inter turns faults may be difficult to detect due to the low level of the corresponding line current. On the other hand, with frequency power conversion we need to take in account the limited value of the short circuit current with its possible collapse within 1s. Consequently, for transformers the use of two winding differential relay (ANSI 87T protection) and restrained earth fault protection (ANSI 64REF) would bring a reliable solution for any kind of faults. To secure the system, additional protections and thermal overload (ANSI 49T) should be installed.

Protection of paralleling operation: During shore start sequence, there is a risk that shore substation closes its main output breaker while ship has already energized the connection cable. To prevent shore to be connected without synchronization to a ship, dead bus verification (ANSI 84) is set on the main output breaker. This protection enables the closing of the main output breaker only if no voltage is detected downstream. During parallel operation of shore substation with ship generators, a reverse power protection (ANSI 32) is set on the main output breaker of shore substation to prevent the ship to provide power on the grid or to supply a fault on shore side. Moreover, to guarantee acceptable voltage tolerance to ship loads, under/over voltage protection (ANSI 27 and 59) and under/over frequency protection (ANSI 81 U/O) are also set on main shore output breaker.

Connection cable continuity monitoring: In the case of breakdown or high impedance (poor contact) of the ground conductor, the bonding potential between shore and ship could exceed 50V during ground fault and be dangerous for operators (Fig. 15). As the shore-to-ship cable is handled many times, for each ship connection, this risk is not minor. Hence, a ground check system is installed between shore and ship to detect the ground conductor failure. The principle is shown in Fig. 16; a current is injected in an additional pilot wire and passes through the ground conductor; if a failure occurs on the ground conductor, the ground check system will trip the main circuit breakers on both sides. There is also the potential risk of a power connector resistance deviation (due to poor contact) that could result in plug arcing phenomena. To bring a correct detection of that kind of failure, negative sequence overcurrent protection (46) is set on shore main output relay.

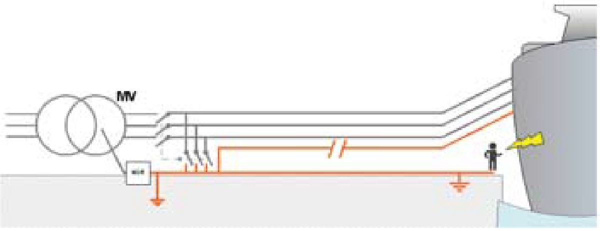


Fig.15. Ground conductor failure [18].

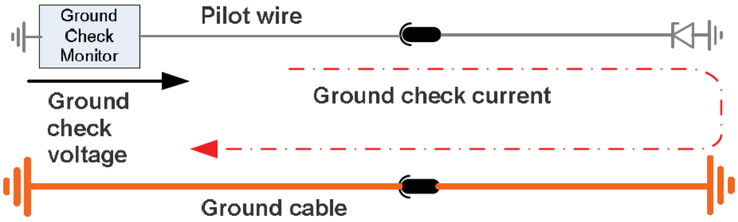


Fig. 16. Ground check system [18]

2.4.3 Other safety systems

Handling, connection and disconnection of MV plug induces electrical hazards. As shown in Fig. 17, when performing a connection/disconnection, the operator has access to power connectors, and thus can experience a shock hazard if the power connectors are not disconnected and not earthed. The possible risks are summed up hereafter:

- fail to disconnect from shore substation,
- fail to disconnect from ship power system,
- fail to discharge the MV cable.

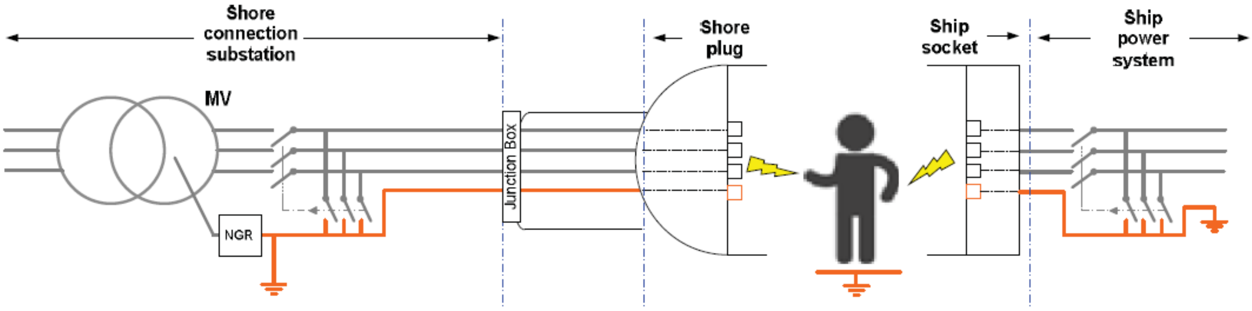


Fig.17. Electrical hazards during connection/disconnection [18]

The main shore connection safety functions are specified as following:

- Safety function F1: disconnection of MV plug and socket from the sources,
- Safety function F2: discharge of MV cable,
- Safety function F3: prevent access to MV socket and plug while not grounded.

IEC/ISO/IEE 80005-1 defines specific measures to prevent these risks. The recommended measures are classified as follow in the standard:

- emergency shut down,
- conditions for shore connection start sequence (conditions on main breaker closing and earthing switches opening),
- conditions for plug handling during plugging and unplugging (opening disconnector and closing earthing switch on both side).

Generally, shore operation will be performed by non-qualified electricians' teams. Consequently, all the elementary operations shall be simple and secured. That is why the safety during shore connection and disconnection is achieved by the integration of two basic concepts:

- operating instructions and procedures,
- automatic interlocks managed by a safety system (see Fig. 18).

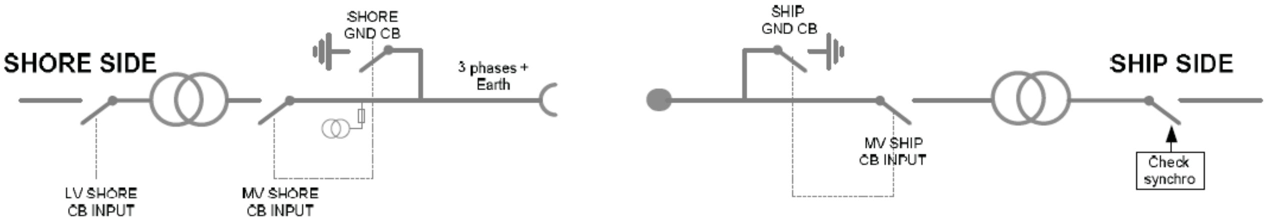


Fig. 18. MV shore to ship connection architecture [18]

The aim of automatic interlocks is to prevent all the risks intrinsic to the MV plug handling, during plugging and unplugging phases. Here after are mentioned, the main actions to guarantee safety:

- during MV plug handling:
    - permit the plug handling when shore circuit breaker is locked opened and to maintained earthing switch closed,

-
    - prevent to handle MV plug if not earthed,
- during MV plug plugging
    - prevent the access to MV socket if not earthed,
- during MV plug unplugging before power connectors disconnection:
    - open the circuit breaker and the disconnector automatically on both sides,
    - close the ground switch automatically on both sides.

Safety system (Fig. 19) is ensured by pilot wires which are a part of the power cable. During plug disconnection, the plug design permits to first disconnected the pilot contacts to shut down and secure the installation before the power connectors disconnection.

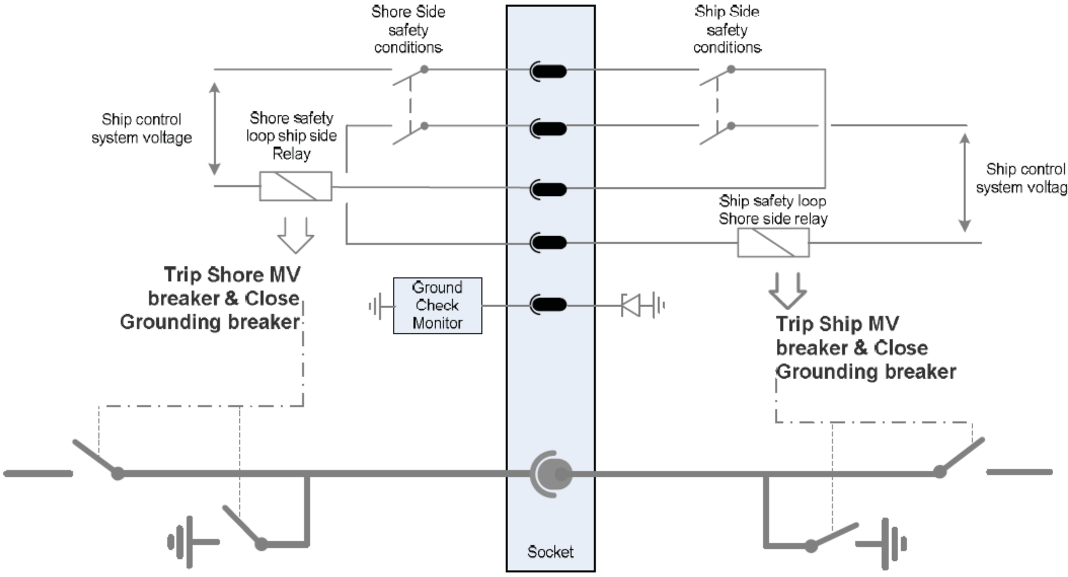


Fig. 19. safety loops diagram [18]

Loops and relays:

- a safety loop for shore connection substation and 1 safety loop for ship switchboard,
- a safety loop is basically composed of a DC power supply and a relay,
- when the relay is no longer supplied, its auxiliary contacts disconnect the MV cable (by opening the main breaker) and ground the MV cable (closing ground switch).

Emergency stops:

- e-stops on shore and ship side trip the 2 safety loops.

2.5 Some open issues in HV shore connections

HV shore connections still present some specific problems concerning the human safety, that require additional investigation. The most significant ones are depicted in the following.

2.5.1 The Interference of the Ship-Shore Bonding on the Cathodic Protection

The ships commonly require some method of protection in regards to corrosion, being them immersed in a conductive element where several different metals and elements are also immersed. This is obtained through different technical means. Cathodic protection on small ships is often implemented by galvanic anodes attached to the hull, which corrode in place of the ship and need to be substituted periodically. Impressed Current Cathodic Protection (ICCP) is used for larger vessels, where the electron flow causing the corrosion issue is counterbalanced by an equal and contrary one, applied by a suitable system. ICCP systems have now been fitted to thousands of vessels of every type around the world. ICCP is also a common anti-corrosion engineering practice for the jetties having submerged steel structures (i.e. steel foundation poles, sub-water metallic carpentry or reinforced concrete). On both, ships and jetties, the injected DC current magnitude depends on several environment variables, i.e. structure extension, type and maintenance degree of the coating, water salinity and so on; however, the total amount of the current required may be relevant. For instance, typical current density for a ship may be 25-30 mA/m2, while for a jetty may be around 100 mA/m2 [19]. As consequence of the large surfaces involved, a total of several tens, or sometime even hundreds of Amps, may be needed for corrosion protection.

When a conductive bonding between the ship and the shore, not at the same potential, is applied, a large current may flow through. This is the case of using a HV shore connection system, which also requires the presence of an equipotential bonding among the shore and the ship, as above-mentioned. In such a case, the cathodic protection rectifiers of the jetty and/or of the ship represent the current sources. Leakage given by power sources or stray currents due to galvanic potential differences between ship and shore are plausible eventualities, but usually their effects are smaller and of less consequences than the ICCP ones.

For example, let us consider a ship running ICCP, moored at a jetty provided with steel poles foundation, as depicted in Fig. 20. The foundation poles are (intentionally or de facto) electrically connected to the shore grounding. Then, a bonding cable will bridge the jetty structure and the ship hull, not at the same potential. The ICCP is design to prevent corrosion, by mean of an electric field sustaining proper DC stray currents from the ship anodes to the hull surface, in order to keep the hull potential (with respect to a reference electrode placed in the water), within a correct negative range, between desired upper and lower limits. The jetty, through the bonding, becomes electrically part of the hull and a fraction of the injected stray current will close to the jetty, returning to the negative pole of the ship rectifier through the bonding cable itself. We may also say that the ship’s ICCP, in case of bonding, is trying to protect the jetty as well.

An opposite, but similar, case occurs if the jetty has an ICCP system and the ship has not one. This situation is reported in Fig. 21. In this second case the shore ICCP tries to protect the ship hull and the bonding is allowing the current return from the hull to the negative pole of the shore rectifier.

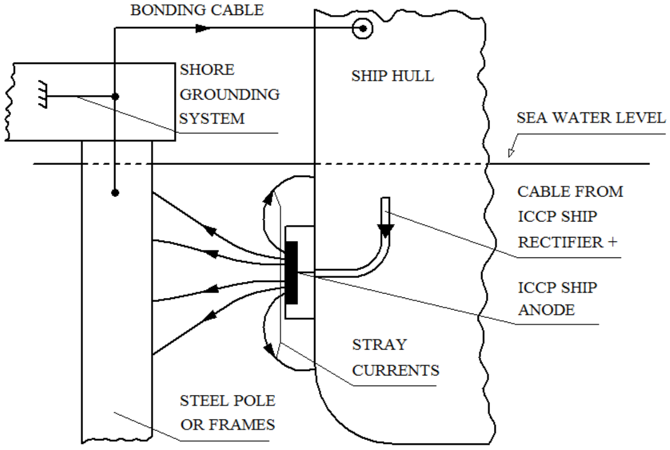


Fig. 20. Ship running ICCP at berth [14].

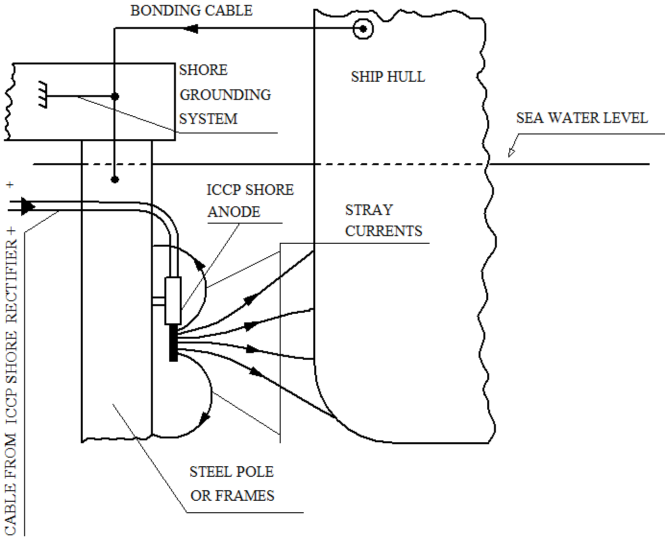


Fig. 21. A jetty running ICCP with a ship moored alongside [14].

A much more complex case is when both, the ship and the jetty, are running ICCP, because of the overlapping of the two situations above. In this case the resulting total current distribution depends on the mutual positions and location of the ship and shore anodes, as well as on the respective magnitude of the injected currents. The general consequence of ICCP and bonding coexistence may be resumed as follows.

In case of ICCP, the bonding cable becomes a permanent active current-carrying conductor. The distribution of the protection currents of ship and/or of shore as well as the electric field in the water is disturbed and the corrosion protection of vessel and shore is no longer warranted as long as the ship is at berth. Furthermore, there is a realistic risk of electrical arcing at the connection/disconnection of the bonding wire, given by possible electrical potential differences between ship and jetty. The last may be of special relevance in case of hazardous flammable atmosphere presence, as is in case of oil or gas tankers as discussed in one of the following sections.

In order to avoid any corrosion problem and transferred touch potentials, while ensuring the required safety standards, the following solutions may be used [17]:

1. Implement an active or passive cathodic protection (Fig. 22), which may lead to the issues above depicted;
2. Adopt a different configuration from the TN-system double grounded.

To avoid the interconnection of the GS and the CEN, and thus the origination of the currents between ship and shore that may cause corrosion, two practicable solutions may be implemented:

- two independent grounding systems (on the shore-side and on the shipside), that is a TT-systems for a ground fault on the shipside;
- a galvanic separation of the two networks via the interposition of a dedicated transformer in a TN-island system for a ground fault on the shipside.

As shown in Fig. 23, the first solution consists in the physical separation of the two grounding systems, CEN on ship and GS on shore, eliminating the PE interconnection. The shore-side neutral point of the transformer is still connected to the ground via a dedicate resistor (R), whose value however should not be varied according to the type of ship docked, since the two systems (CEN and GS) are now independent. The CEN and GS are directly involved in the fault path for a ground fault on the shipside, constituting a TT system and the loop impedance is practically equal to $Z_s=R+R_{GS}+R_{CEN}$. This condition presents so the possibility of touch voltages not easily predictable. Differently, for a ground fault on the shore-side the ECPs are connected to the same-grounded point of the neutral, constituting a TN-system and the loop impedance is practically equal to $Z_s=R+R_{GC}$.

The possible difficulty to detect the first fault on ship side may originate higher touch voltages at the second fault. However, removing the interconnection of the two grounding systems, it eliminates the basic path for the DC currents and inhibits ground faults interferences with transferred potentials.

Fig. 22. In left side: Cathodic protection with sacrificial zinc anodes - In right side: corroded propeller [17].

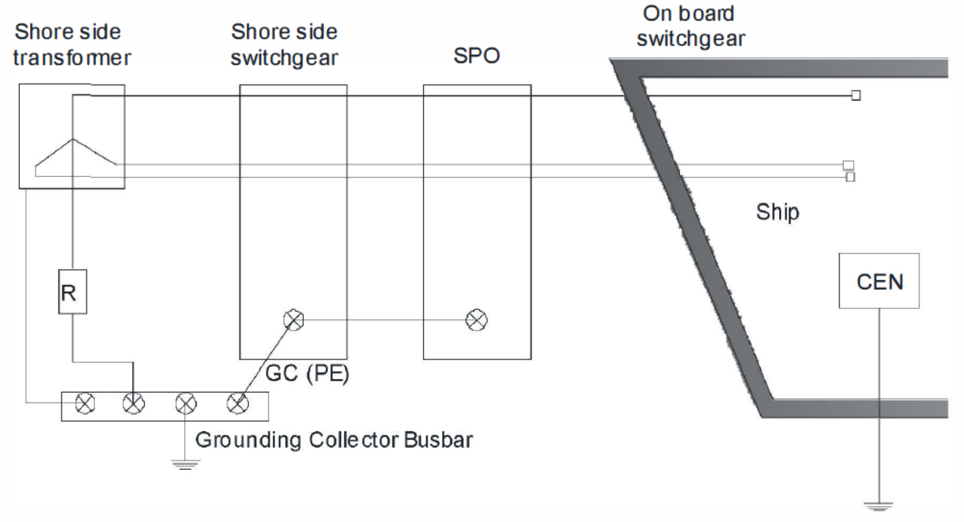


Fig.23. TT-system [17].

The TN-island solution, without requiring external galvanic protections, is able to ensure at the same time the two key requirements for a marine application: electrical safety avoiding possible touch potential transfer on the shipside and the elimination of any path for the DC currents. This solution is suggested by the IEC/ISO/IEEE 80005-1 exclusively for cruise ships, since these are expected to be docked for longer periods, and thus are more incline to fault exposition and corrosion problems. This solution however can be applied to any kind of ship, in particular to the container ships.

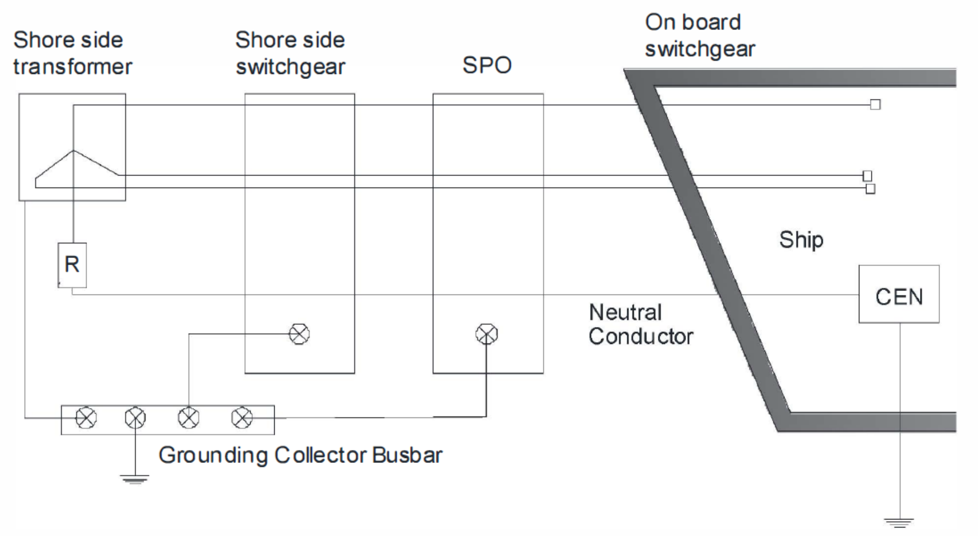


Fig. 24. TN-island system [17]

The system configuration consists in a TN-system with the neutral point connected to ground in a single point. When a cruise ship is docked, the neutral point of the shore-side transformer is disconnected from the shore's collector bus bar and connected, via the resistor R, to the ship's grounding system (CEN) (Fig. 24). The two grounding systems are then operated independently one from the other, where the more critical shipside system is characterized opportunely as TN-island system, while the shore-side system represents an IT-system. This approach is also used in low voltage shore power applications [19, 20].

As shown in Fig. 24, the interconnection between the resistor R and the ship's CEN does not act as an equipotential bonding, the conductor is then a neutral one. The monitoring process of the TN-island system ensures an increased reliability since the ground system is connected in only one point, corresponding to the ship's hull. The neutral conductor characterizes then the only path for the fault current on the shipside that can be easily detected, even in the event of a first fault characterized by a relevant resistance. In any case, the fault path excludes the two "ground" resistances of the ship and of the GS. With regards the presence of DC currents, these are reduced to a negligible value since there is no intentional connection between the ship's hull and the shore-side grounding system.

Fig. 25 shows the presence of a dock ground switch #4, that due to the interconnection with both #1 and #3, ensures that the connection of the neutral line to the ship's grounding system or to the shore grounding system, depending on the

energization state of the system. A ground fault on board the ship generates an instantaneous tripping even of the protective devices, with an immediate shut down of the operations, typical performance of a TN -system. This ensures acceptable touch voltages even in the event of a fault.

For the protection of ground fault in the shore-side section of the system, all the bulks placed between the transformer and the ship have to be connected to the shore-side grounding collector, avoiding however a connection to the ship's hull.

The Annex C of the above-discussed standard shows the configuration of Fig. 25 that proposes the special case of cruise ships. A TN-island system may then combine the advantages of inhibiting the circulation of DC currents between the hull and the shore-side grounding collector, while at the same time ensuring all the safety requirements, especially around the shipside, critical area, and avoiding transferred touch potentials.

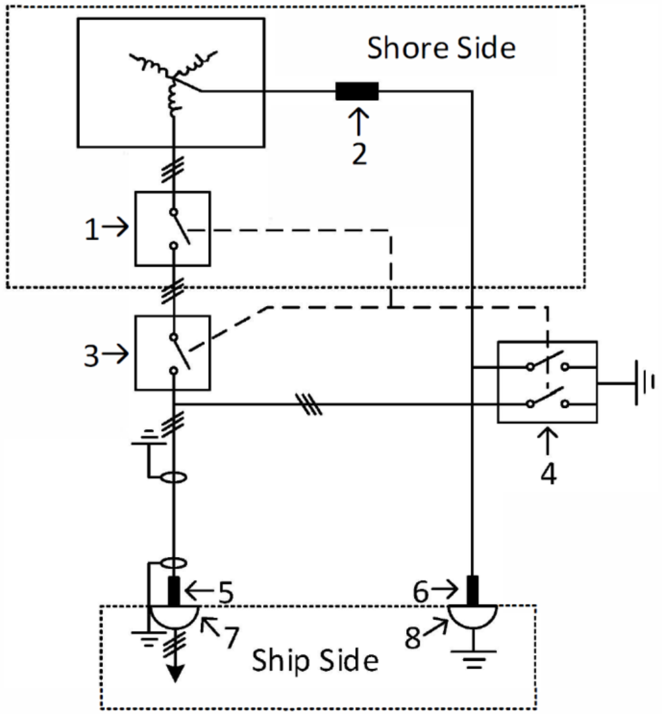


Fig. 25. Simplified scheme as prescribed by Annex C of IEC/ISO/IEEE 80005-1 [17]
1: Transformer secondary circuit breaker. 2: Neutral grounding resistor. 3: Dock disconnect switch, 4: Dock ground switch. 5: Power plug (x4), 6: Neutral plug, 7: Power socket (x4), 8: Neutral socket

2.5.2 The Ship-Shore Bonding in case of Flammable Products Tankers and LNGC

Oil and petroleum products tankers, as well as Liquefied Natural Gas Carriers (LNGC), are a particular but widespread, class of vessels. The High Voltage Shore Connection of these ships is, as for the remaining type of vessels, also covered by the IEEE/ISO/IEC Standard 80005-1 [10]. Consequently, according to this Standard, in case of HVSC the ship-to-shore equipotential bonding is mandatory for tankers and LNGC, as for any other type of vessel.

With the aim of excluding the risk of tanker fire/explosion, one possible solution is to prevent a source of ignition and a flammable atmosphere, being present at the same moment in the same area. The electricity, in all its forms, is one of the major sources of ignition. Among all the possible electrical sources, a well-known one is the static electricity. Many crude oils and liquid hydrocarbon products derived from it are flammables and produce static electricity during theirs handling. Electrostatic discharge may be a source of ignition in ship-shore cargo loading or unloading operation. There are three basic stages leading up to a potential electrostatic hazard: Charge separation, Charge accumulation and Electrostatic discharge. Electrostatic discharge occurs when the electrostatic field becomes too strong and the electrical resistance of an insulating material suddenly breaks down. When breakdown occurs, the gradual flow and charge recombination associated with relaxation is replaced by sudden flow recombination that generates intense local heating (e.g. a spark) that can be a source of ignition if it occurs in a flammable atmosphere. In the past, to prevent this risk, it was usual to connect the ship and shore systems by a bonding wire via a flameproof switch before the cargo connection was made and to maintain this bonding wire in position until after the cargo connection was broken, but unfortunately the practice proves that the use of this bonding wire had no relevance to electrostatic charging. Though static electricity and charge accumulation is commonly prevented connecting an object to the earth, experience said that the use of a ship-shore bonding cable has no effectiveness for [14].

As previously discussed, an electrical source of ignition may also be the cathodic protection (CP) taking into account possible electrical potential (ship/jetty) and consequent risk of electrical arcing at the manifold while shore hose or loading arm are connected or disconnected. In effect, a very low resistance connection tanker/shore is provided by an all-metal loading or discharge arm: this constitutes a concrete danger of an incendiary arc when the consequent large current is suddenly interrupted whereas the arm is connected/disconnected at the tanker manifold. Being the ship/shore bonding cable discouraged by the applicable International Standards and worldwide practice, the terminal operator should guarantee that cargo hose strings and metal arms are equipped with an insulating flange. This is necessary to avoid an electrical flow between a tanker and a berth during the shore hose's or loading arm's connection/disconnection. It is important to remark that any electrically conducting path between tanker and shore (for instance mooring wires or a metallic ladder or gangway) could be responsible of a current flow. Therefore, such connections should be insulated to avoid draining the jetty cathodic protection system by the added load of the tanker's hull (and/or vice versa). Technical and scientific details about, may be found in "A Justification into the Use of Insulation Flanges (and Electrically Discontinuous Hoses) at the Ship/Shore and Ship/Ship Interface" [20].

To fix a guide in this field, the standard, "International Safety Guide for Oil Tankers and Terminals" – ISGOTT [21] states:

Large currents can flow in electrically conducting pipework and flexible hose systems between the ship and shore. The sources of these currents are: cathodic protection of the jetty or the hull of the ship provided by either an impressed current system or by sacrificial anodes or stray currents arising from galvanic potential differences between ship and shore or leakage effects from electrical power sources………………To prevent electrical flow between a ship and a berth during connection or disconnection of the shore hose or loading arm, the terminal operator should ensure that cargo hose strings and metal arms are fitted with an insulating flange…………… In the past, it was usual to connect the ship and shore systems by a bonding wire via a flameproof switch before the cargo connection was made and to maintain this bonding wire in position until after the cargo connection was broken. The use of this bonding wire had no relevance to electrostatic charging. It was an attempt to short circuit the ship/shore electrolytic/cathodic protection systems and to reduce the ship/shore voltage to such an extent that currents in hoses or in metal arms would be negligible. However, because of the large current availability and the difficulty of achieving a sufficiently small electrical resistance in the ship/shore bonding wire, this method has been found to be quite ineffective for its intended purposes but has itself created a possible hazard to safety. The use of ship/shore bonding wires is therefore not recommended………………

While some national and local regulations still require mandatory connection of a bonding cable, it should be noted that the IMO Recommendations on the Safe Transport of Dangerous Cargoes and Related Activities in Port Areas' (1995) urge port authorities to discourage the use of ship/shore bonding cables and to adopt the recommendation concerning the use of an insulating flange.

Recommendations discouraging the ship/shore bonding wire for oil and petroleum tankers, exists not only in ISGOTT and IMO, but also in similar Standards of other Bodies. See for instance the ISGIN International Safety Guide for Inland Navigation Tank-barges and Terminals [22]. Similarly, also the applicable ISO Standard for liquefied natural gas carriers LNGC and ship-to shore interface and port operation [23] clearly discourage the bonding. In fact, the ISO 28470 explicitly states:

Due to the difference in electrical potential between the ship and the jetty, there is a risk of an incendive arc when the transfer arms are being connected or disconnected. Arrangements should be made to avoid the risk of arcing

from this source by the installation of an insulating flange in the transfer arm Care should be taken that the insulation flange is not shorted out by the use of electrically continuous hydraulic hoses.
CAUTION — The use of a ship-to-shore bonding cable is not only considered to be ineffective but can also be dangerous if it breaks in a flammable atmosphere.

Then, there is an apparent conflict as far as ship-shore bonding is concerned, in case of HVSC for tankers or LNGC carries. The IEC/ISO/IEEE Standard [10] prescription of an equipotential ship-shore bonding for human safety is undoubtedly correct and based on self-understandable solid arguments. But also, the ISGOTT and ISO position in discouraging the bonding is based on shareable safety arguments. Of course, remembering that to eliminate the risk of fire and explosion on a tanker it is necessary to prevent a source of ignition and a flammable atmosphere being present in the same place at the same time, if the bonding (and the whole HVSC shore equipment) is located in a no hazardous area, the conflict may bypass. In fact, the HVSC Standard states:

…Electrical equipment in areas where flammable gas or vapor and/or combustible dust may be present: HVSC equipment shall be located outside the hazardous areas of the ship and shore facilities under normal operating conditions, except where it is shown to be necessarily located in these areas for safety reasons…

The point is that the classification of the hazardous areas on shore, as well as the type of admitted and forbidden electrical installations within, is depending on national and local requirements differing all around the world. Once a tanker, or a LNGC, is moored at berth, the location and characteristic of the hazard sources of the jetty (i.e. vapors vents, valves, manifold, flanges, sampling points, etc.) and the ones of the ship has to be considered together. The overlapping implies a considerable situation of variability and uncertainties in the overall hazardous areas' classification. In essence, even if desirable and correct, a classification of areas valid for all possible ship-shore situation may be a very complex solution problem.

2.5.3 The electrical safety of ship-shore bonding in presence of a HV point of common coupling of the port with the power grid

In case of HVSC, relevant electrical powers (1–20 MW) per single ship are usually required when all-electric cruise liners, commercial ships or even some types of naval vessels are moored at berth. Depending on the number of vessels served, the sum of HVSC power demand in addition to the one for conventional dock services may easily result in a total of several tens of megawatts within a single port area. Such an amount of power may be supplied from a HV line at a voltage exceeding 100 kV (the effective voltage being case dependent according to the local standards; for instance, in Italy, usually 132 or 220 kV). Differently from MV, the HV networks exceeding 100 kV are usually operated with solidly grounded neutral, that means, in case of a phase-to-ground fault of the primary supply within the port grounding, a fault current of several kA will establish (in Italy, for example, values from 10 to 20 kA are common).

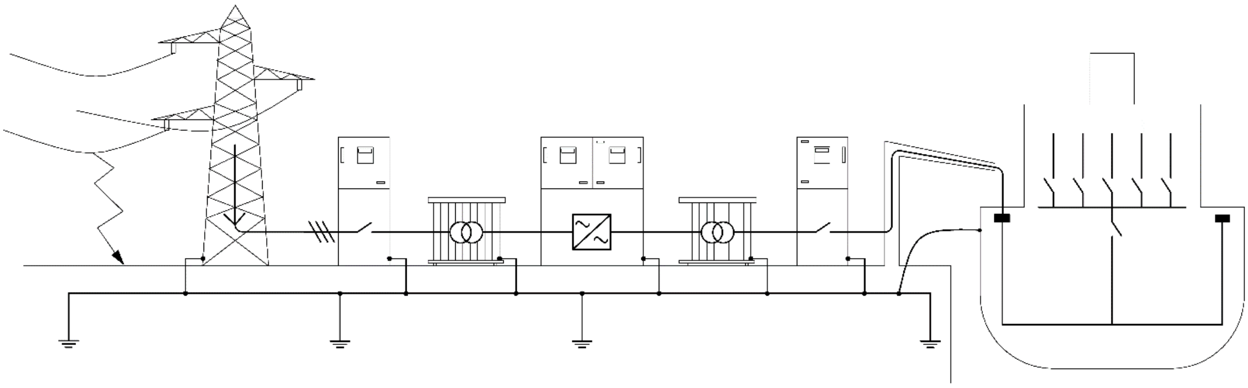


Fig. 26. Port with HVSC system supply by a HV > 100 kV primary line with a single-phase fault at the delivery point [14].

As widely known, the earth fault current can split and not all of it flows through the local ground, closing to the remote earth. Indeed, a part (not easy to be quantified in all cases) may returns directly (galvanic way) to the remote neutral through different paths, such as sky wires, cables shields, etc. Anyhow, according to the local and national standards considering the maximum expected ground fault current flowing through the port roads, the port grounding systems must be designed and tested to be safe in terms of touch and step voltages. Certainly, the arrangement of each individual port is case dependent, but theoretically a port facility layout demanding power above some tens of MVA will result similar of what depicted in Fig. 26.

Commonly, an all-interconnected buried net constitutes the grounding system of the supplied facility, either in case of a large industry or in case of a port. A very simple rule to ensure the electrical independence is well known in practice and it states that the two individual grounding nets should be distant at least five times the dimension of the larger net, even if the grounding system consists of unintentionally connected sub-systems (considering the safety issue, not an advisable practice in most cases). The above is particularly true for cruises terminals. Taking into account touristic applications, generally the passenger terminals are just located in the nearby of city centers instead of remote large port areas. Therefore, the separation of the HVSC grounding grid from the grounding grid of the local power substation is inconceivable. Furthermore, there are not only intentional connections between grounding sub-grids voluntarily made, but also unintentional ties (for example pipelines, railway tracks, buried metallic structures, etc.) connecting the bulk substation grounding grid with the HVSC installation. This is the reason why the shore grounding net (together with all the relevant incorporated metallic buried) is forming a unique galvanic connected rod. The direct consequence of this aspect is the generation of hull touch voltages, when a phase-ground fault at the local primary side substation involves the whole shore grounding as well as the bonded ships. Due to the bonding between the hull and the shore, in practice a shore-connected ship becomes a peculiar appendix of the port earth system. Not only, even ships not electrically shore supplied but just moored nearby may become part of this system, in case of unintentional but effective bonding existence (i.e. mooring wires or a metallic ladder or gangway, or similar conducting structures).

The vessel hull is a peculiar road because of its coating. Theoretically, assuming the hull where perfectly insulated by a coating of infinite (in practice very high) resistivity paint, in case of a phase-ground fault on the primary HV line there would be no conduction at all in the sea to the remote electrode (neglecting the capacitive current). The hull in this case will assume the same potential of the shore grounding system at the bonding cable connection point (i.e. the full potential difference will stay across the coating itself). On the opposite, a totally bare hull will generate a flat and negligible electric gradient of potential around the ship.

In reality, we have something in between of the two above extreme cases. Like it happens in the majority of the anti-corrosion coatings used for pipelines and similar industry applications, also a ship's painting is an insulating medium with a resistivity value that changes from the usually very good one measurable at lab on a sample coming in, to the actual existing on an aged vessel's hull in service. Once a ship's painting having a certain laboratory measured resistivity, is applied on a metallic surface, its bulk average resistivity on site falls down strongly (i.e. orders of magnitude): this phenomenon depends on the distribution of "holidays" (in the jargon of corrosion engineering), which are micro defects within the coating itself.

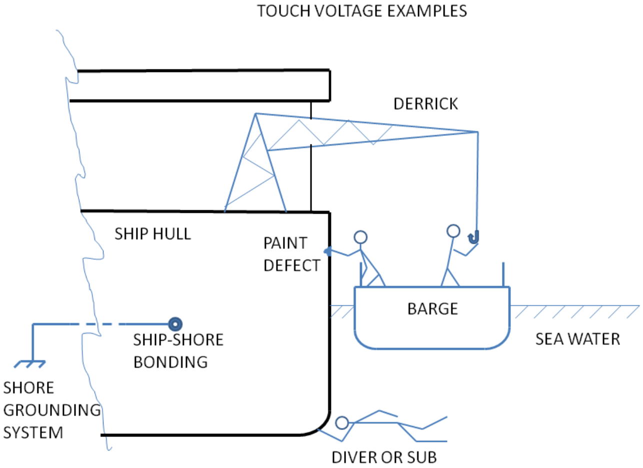


Fig. 27. A jetty running HVSC with a ship moored alongside [14].

The coating ageing and the filling of the holidays by water during the vessel life contribute to further progressive decrease of the bulk resistivity values. In practice, the coating of a ship still remains during its life fundamentally a semi-insulating layer, and a ship's hull situation is de facto something variable between the two extremes: totally bare and perfectly insulated metal body.

On localized points of the hull, a direct contact between a human body and the metallic part of the hull is possible during the phase-ground fault on the primary power supply. This may happen on surface scratches, or even at local breakdown points where the difference of potential exceeds the coating electric rigidity. Some potential cases are as reported in Fig. 27.

A study reports the simulation results in case of standard dimensions ship, bonded with a shore grounding grid, where a 10 kA current reclosing to a remote earth has been injected by a fault [24]. In the study, the coating resistivity has been varied from the value of a perfectly new one, to a very bad maintenance one; likewise, also the water resistivity has been varied from fresh to very salt water, to consider different water conductivity as well. Different distances between the ship and the shore ground grid have also been considered. The voltage gradients in the water all around the vessel have been computed by finite elements calculation. The computed difference of potential between the hull and a point 1 meter far away in the water are reported in Figs. 24. (In the captions they are conventionally called for simplicity "touch voltage" instead of, may be more correct voltage gradient, having in mind situations where a human could be positioned like in Fig. 27. Obviously, to talk of "touch-or step-voltages" in water is misleading in respect to the common understanding for.

The simulation result (Fig. 28) is surprising: in case of well-coated vessels, a 10 kA single phase fault may generate a difference of potential between hull and a point in the water (1 m far away from hull) in the range of 2 or 3 kV. Of course, reported results are obtained considering the schematic case of study presented. Thus, for a given port and a given ship, proposed analysis requires to be particularized to the specific. However, the study recalls the attention on a phenomenon that may lead to hazardous situations. Actually, under quite realistic conditions that are usual for berthing operations, the developed simulations have demonstrated how some dangerous issues may arise. To face the problem, it is possible to summarize two categories of possible actions: 1) to establish adequate operative rules or 2) to limit the portion of fault current that flows through the port grounding net up to the remote earth.

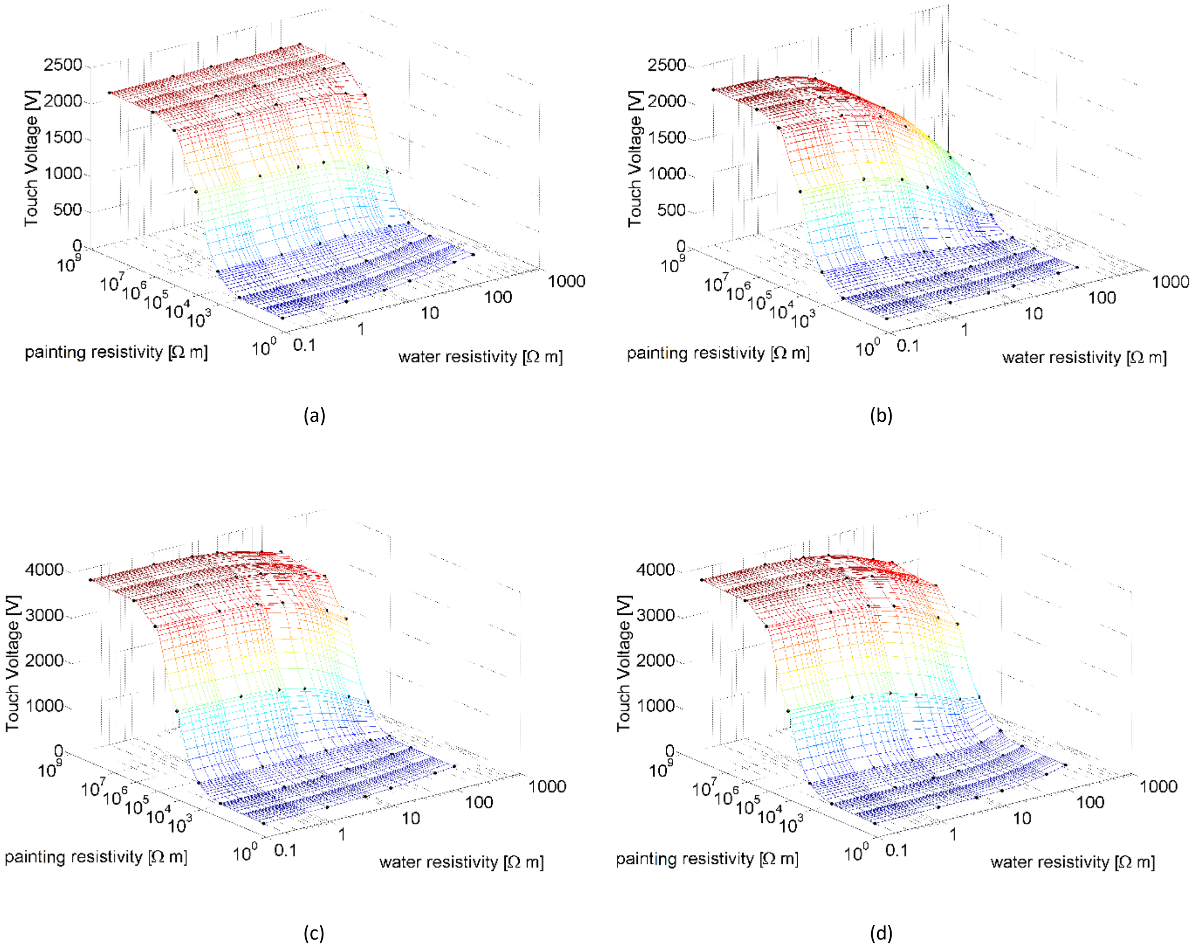
1) Considering operative rules, an obvious possibility is to forbid barges and swimmers to approach the ships when a cold ironing is being achieved and ships are shore bonded. Unluckily, such easy practice in theory is not applicable in reality. Indeed, forbidding service barges in the nearby of shore-connected ship would impair important port operations (such as bunker, garbage collections, repairs, etc.). While an equipotential bonding between ships and servicing barges, if practicable, would improve safety in some cases, it will just relocate the problem around the barges themselves. In addition, it would require proper connection points along the hull at different levels and locations, which are not presently provided on the coated hull of the vessels.

2) More practicable are electrical measures limiting the phase-to-ground fault current reclosing to the remote earth through the port's grounding roads. They are two main possibilities to reach the goal: a) to create a very low impedance conductive connection path between the local port grounding system and the remote power supply company's earth where the remote HV transformer neutral is grounded. The connection may consist in the existing line's shield/ground wire, or in an "ad hoc buried" conductor, or both. However, the effective split factor is critical for the knowledge of the real current magnitude leaving the port substation road, then is as well critical for the human safety evaluation. Unfortunately, accurate computing is not easy at all in case of an HV line, as explained for instance in [25]; b) to increase the zero-sequence impedance of the port's HV power supply system by a resistance connected neutral. The last solution looks much more practicable and efficient than the first one.

Both the above actions, if implemented, require that preventive technical and economical agreements are established between the port authority and the electrical power supply company, before the construction of the HV power line.

The magnitude of a single-phase to earth fault current in an HV power system depends upon the type and extension of the network and in particular on its zero-sequence impedance, that is in turn linked to the type of the power system neutral grounding. Historically there has been a worldwide gradual trend in power system's practice from ungrounded, to resistance grounded, to solid or effective grounded neutral with the growth of systems themselves, both as to mileage and voltage. Today, solid neutral grounding is practically everywhere the rule for systems exceeding 100 kV. A saving in system cost become available by the use of transformers having the insulation graded from the line terminal to the neutral, if the neutral was solidly grounded. Nevertheless, the use of a resistance grounded HV line, just for the power supply of a port remain a practicable option to limit the single-phase fault current. As a drawback of course, the higher the resistance value the lower the fault current, the higher the cost for reinforcing line and transformers insulation.

An above based solution case study has been presented in [26] and here is briefly recalled. Let us consider a situation like the one reported in Fig 29. To limit the phase-to-ground fault current, the solution proposed is to use at the supply power company (i.e. at the beginning of the HV supply line) a HV/HV y-Δ-y (wye-delta-wye) transformer with secondary resistance grounded neutral and with the delta coil without load connected. The delta tertiary is necessary to allow the zero sequence currents flowing between the supply and the port stations. The circuit arrangement proposed is just one of the possible solutions; different circuit arrangements are also possible. In the above-mentioned case study, it is assumed a phase-to-ground fault current of 10 kA at the port power delivery point. The moored ship's hull is assumed to be the one considered in the former reported paper [24].



(a) (b)

(c) (d)

Fig. 28. Voltages, between the hull and a point at 1 m distance in the water, computed in case of a phase-ground fault with a current of 10 kA [24]
(a) shore ground grid located 5 m far from the ship, potentials at sea side, (b) shore ground grid located 5 m far from the ship, potentials at berth side,
(c) shore ground grid located 100 m far from the ship, potentials at sea side, (d) shore ground grid located 100 m far from the ship, potentials at berth side.

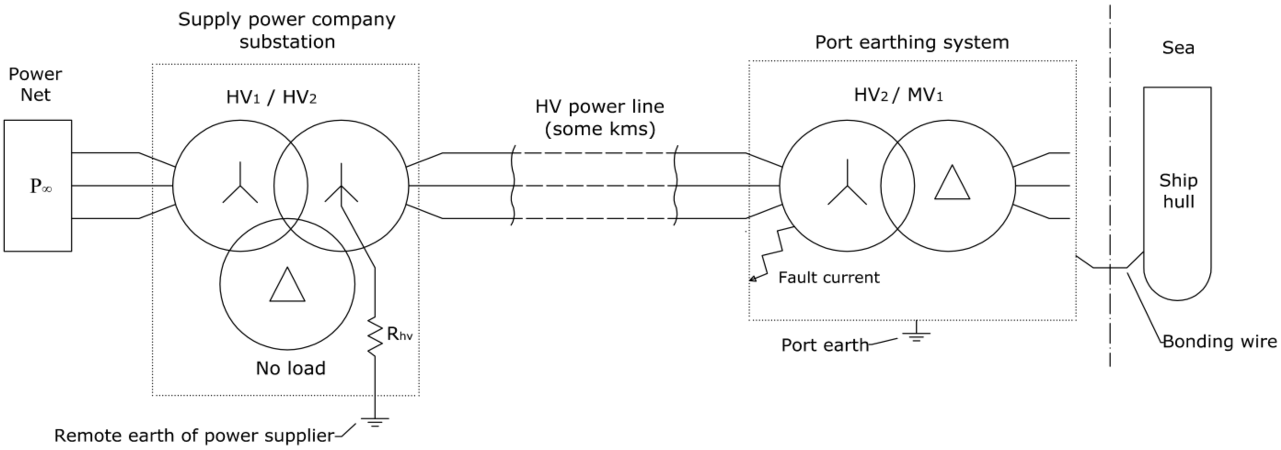


Fig. 29. Port supply line with y-Δ-y (wye-delta-wye) transformer with neutral resistance grounded at the supply power company's substation [26].

A voltage gradient exceeding 2000 V per meter, (vessel with a good condition coating and in ocean salt water) is supposed to be computed by simulations. Assuming that a reduction in the above gradient to a safe value is sought (for instance, from 2000 to 30 V per meter), being the relation current-voltage practically linear it is immediate to find that the single phase-ground fault current must be reduced from 10 kA to 150 A. Considering the previous hypothesis, according to Fortesque’s analysis the phase-to-ground fault current I_{k1} can be calculated.
In the case study [21] the calculation of I_{k1} was done for a port supply with the following main data:

- a power supply net 230 kV 60 Hz, with short circuit power 6000 MVA;
- a power company station 230/138 kV with a transformer of 300 MVA;
- a 138 kV line with a length of 10 km, connecting the power company substation to the port;
- a port primary station 138/34.5 kV with a transformer of 100 MVA;
- typical electrical parameters values consistent with the above data have been assumed for calculations.

Computing has been done first by means of Fortesque's equations. It has been proved how, grounding the neutral with a resistance of 527 Ohm at the power company transformer, the expected single phase fault current from 10 kA slows down to the wanted 150 A, in agreement with the objective. Afterwards, the system with the neutral resistance has been then simulated in the time domain; the simulation performed has confirmed the previous result.

3. LOW VOLTAGE SHORE CONNECTION

A Low Voltage Shore Connection (LVSC) is a shore connection system using either 400, 440, or 690 V cables to connect shore and ship. It is intended to deliver low power levels (less than 1.5 MW), to small ships and pleasure crafts.

The design concept for these systems is contained in the current LVSC draft standard, International Electrotechnical Commission (IEC)/IEEE 80005-3. This application, while not being standardized at international level until now, is usually partially covered by national standards. In Italy rules about the Low Voltage Shore Connections with either 230/400 V (single/three-phase) cables are present in CEI 64-8, Section 709. However, these rules cover only pleasure boats, thus considering only a limited power level range (up to some tens of kW). The general rules for the construction of LV land connections in the Republic of Croatia are established in accordance with European Standard, which establishes Technical Requirements for Inland Navigation vessels (ES -TRIN). For currents up to 125 A, they comply with the requirements of European Standards EN 15869-1: 2019 and EN 15869-3: 2019 and for currents above 250 A, with the requirements of European StandardsEN16840: 2017.

The presence of different standards in different countries is an issue for the marine industry, which is required to design and qualify separately each product for each geographical area where it is sold. Therefore, during the past years the industry strongly demanded a standard solution to connect low voltage vessels in order to allow interoperability from different vessels and ports, as well people and systems safety. This motivated the development of the new IEC /IEEE 80005-3 standard. While such standard is yet to be published, here some indications about what it will contain are given.

It is relevant to notice that the new standard addresses only the topics that are not currently addressed by other IEC standards. Therefore, to be fully understanded and applied it requires also the following referenced documents:

- IEC 60034, Rotating electrical machines
- IEC 60076, Power transformers
- IEC 60079 (all parts), Electrical apparatus for explosive gas atmospheres
- IEC 60092-101, Electrical installations in ships – Part 101: Definitions and general requirements
- IEC 60092-201, Electrical installations in ships – Part 201: System design – General
- IEC 60092-301, Electrical installations in ships – Part 301: Equipment – Generators and motors
- IEC 60092-401, Electrical installations in ships – Part 401: Installation and test of completed installation
- IEC 60092-502, Electrical installations in ships – Part 502: Tankers – Special features
- IEC 60092-504, Electrical installations in ships – Part 504: Special features – Control and instrumentation
- IEC 60146-1, Semiconductor convertors – General requirements and line commutated convertors
- IEC 60228, Conductors of insulated cables
- IEC 60204-1, Safety of machinery – Electrical equipment of machines – Part 1: General requirements
- IEC 60309-1: Plugs, socket-outlets and couplers for industrial purposes - Part 1: General requirements
- IEC 60332-1-2, Tests on electric and optical fibre cables under fire conditions – Part 1-2: Test for vertical flame propagation for a single insulated wire or cable – Procedure for 1 kW pre- mixed flame
- IEC 60947-2, Low-voltage switchgear and controlgear – Part 2: Circuit-breakers
- IEC 60947-5, Low-voltage switchgear and controlgear – Part 5-1: Control circuit devices and switching elements – Electromechanical control circuit devices
- IEC 61363-1, Electrical installations of ships and mobile and fixed offshore units – Part 1: Procedures for calculating short-circuit currents in three-phase a.c.

- International Convention for the Safety of Life at Sea (SOLAS):1974, Consolidated edition 201 2009, Ch. II-1/D, Regulations 42, 43 and 45

3.1 Overview of LVSC Power Systems

Shore-to-ship power supply, also called alternative maritime power (AMP) or cold ironing, has been adopted around the globe to reduce, as much as practical, air pollution from ships [10], [27], [28]. Smaller ships rated up to 1,500 kVA require an LV connection between the shore power substation and the ship switchboard, as described in the current draft standard, IEC /IEEE 80005-3. Each power plug and associated receptacle is rated at 500 A continuous and has a 16-kA short circuit rating and a voltage rating of 1,000 Vac. Therefore, for a ship load of more than 500 A, parallel feeders with plug and receptacle assemblies are necessary to meet shore power requirements. Up to five parallel feeders are needed for ships rated 1,500 kVA at 400 V.

Individual plug/receptacle (plug/socket) assemblies and their associated feeder cables require overload and short circuit protection. At present, being the Standard developed in the USA, the reference is made to the rules NEC NFPA 70 [2], but it is reasonable to think that the specific implementation will also be compatible with the IEC regulations in terms of overload and short circuit protection.

One of the possible schemes for protection is to implement individual feeder breakers with a main circuit breaker, so that each individual feeder breaker interlocks with the main breaker such that the main breaker trips without any intentional delay when any of the feeder breakers is activated to open under normal or abnormal fault conditions. Without showing such an interlock scheme between the main breaker and the feeder breakers (which requires additional auxiliary devices), an LVSC block diagram is shown in Fig. 30.

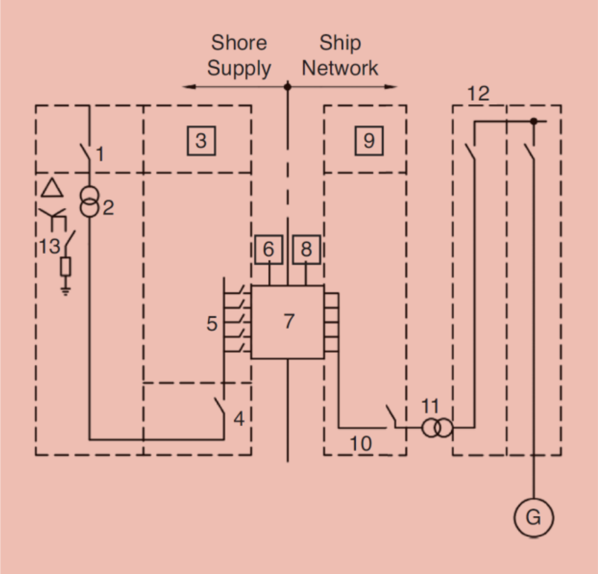


Fig. 30. An LVSC block diagram [30]: the 1) primary breaker, 2) substation transformer, 3) LV switchgear, 4) main breaker, 5) feeder breakers, 6) feeder cables to power receptacles, 7) plug and receptacle assemblies, 8) plug with a flexible cable, 9) ship onboard shore power panel, 10) ship-side circuit breaker, 11) optional ship onboard transformer, 12) synchronizing breaker, and 13) neutral resistor disconnect switch. G: ground.

To provide useful information about the possible implementation of an LVSC system, at first the block diagram for an LVSC power system will be described. Then, a power system protection-relaying diagram that shows the logic of an interlock between the feeder breakers and the main circuit breaker will be shown.

Based on the technical and safety discussion included in the following, the most suitable scheme for an LVSC system, based on the draft Standard, is the use of feeder breakers and a main breaker along with auxiliary control devices for shunt tripping the breakers. Because shore power is interrupted by tripping the main breaker without intentional delay when any of the feeder breakers is tripped, the flow of back feed power from the parallel feeders to the faulted location is stopped with little or no damage.

Some clarifications concerning the parallel use of feeder breakers that are not paralleled within the shore switchboard or switchgear and thus cannot be listed as a unit by LVSC equipment suppliers, as described in NEC 240.8, are also given. This interpretation, which can be considered a violation of NEC 240.8, was brought to the attention of the working members of the draft standard by city inspectors, and should be resolved with the cooperation of the port authority and the professionals responsible for the safe design of LVSC power systems to comply with the draft standard.

The focus here is given to the phase–ground-fault protection scheme by using a neutral grounding resistor that is continuously monitored to automatically trip shore power supply in case the continuity of resistor monitoring is lost. To make the shore power system a high resistance grounded (HRG) system, the neutral resistor is to be sized as 5A continuous, which is adequate to keep the maximum bolted phase–ground fault close to 5.1 A, assuming that the combined ship and shore system charging current is 1 A. To implement an optional ungrounded (IEC designation IT) shore power transformer grounding design, a disconnect switch with a neutral grounding resistor is required, as shown in Fig. 30 (item 13). In addition, a dedicated control interlock scheme is required that will disable automatic monitoring of the shore power neutral grounding resistor as soon as the neutral resistor disconnect switch is opened to operate as an ungrounded system. Since in an ungrounded power system the equipment is subject to the threat of unpredictable transient surges, which can lead to damage and compromise safety [31–34], such application is not recommended. However, the port can work with those ship authorities that require ungrounded shore power supply to equip onboard isolation transformers (item 11 in Fig. 30) and not use a neutral disconnect switch and the associated dedicated interlock scheme needed to operate as an ungrounded power system. In the following, a review of the safety loop control schematic, similar to one used in [10] to enhance the safety of the operators during cold-ironing operation, is also given.

3.2 LV Power Supply System

Fig. 30 presents the major components of the LVSC required onshore and onboard a ship for shore-to-ship power supply. For simplicity of presentation, the figure does not show details of the design of the electrical interlock or communication signal logic required between each feeder circuit breaker and the main circuit breaker to trip the main breaker without intentional delay when any of the feeder breakers is opened under normal or fault conditions.

Continuous monitoring of the substation neutral grounding resistor is commonly employed in the industry for HRG power systems to automatically trip the power on detection of a resistor open-circuit or short circuit condition. The control schematic of such a monitoring HRG system is available [35]. Thus, for simplicity it is not shown here. A neutral disconnect switch providing an ungrounded power system, as required by some ships indicated in the draft standard, adds safety issues for operators when they open and close the neutral resistor disconnect switch to operate the power system ungrounded or HRG grounded under the open or closed position. If an ungrounded shore power substation is not acceptable to a port, then the best option is to request that ship authorities (who require ungrounded shore power supply to ships) install an onboard isolation transformer (item 11 in Fig. 30) and keep the shore power supply system always grounded through an HRG.

A ship connected to an ungrounded shore power supply during cold-ironing operation, whether the ship’s onboard generators are grounded or ungrounded, will be ungrounded, as the onboard generators will be isolated from the LVSC. A faulted condition on an ungrounded power system may result in a three-phase arcing fault during switching activity anywhere in the power system because the neutral is not grounded and stabilized. Some technical experts may conclude that this low-level ground fault current is acceptable since it can be detected by a modern automatic fault-detection control scheme (providing fault location) and then isolated manually to manage onboard critical operation or avoid/minimize arc during fault-clearing action. However, transient overvoltage conditions may cause equipment damage.

The isolation of phase–ground fault on an ungrounded LVSC may endanger a maintenance person who comes into contact with the faulted equipment. For this reason, to minimize phase–ground fault on ships that require LVSC from an ungrounded shore power system, an alternative solution can be proposed: the creation of an HRG grounded power system using a 2A neutral resistor, which is slightly higher than the combined shore and ship system charging current of ~1 A, resulting in a fault current of 2.24 A. If such a solution to lower the maximum phase–ground fault current while keeping a grounded power system is acceptable to ship authorities, then a neutral resistor with two taps of 5 and 2 A can be used to operate shore power systems, which will always be grounded. Sensing and clearing low-level faults is not a problem because a combination of voltage and current relays can be implemented.

3.3 Voltage and frequencies

To enable standardization of LV and link nominal voltage in different ports, LV shore connections shall be provided with a nominal voltage of 400 V a.c. or/and 440 V a.c. or/and 690 V a.c. galvanically isolated from the shore distribution network. The operating frequencies (Hz) of the ship's and shore power systems shall match; otherwise, a shore power frequency converter shall be used.

Operating voltage and frequency shall be checked before connection on board. For vessels repeatedly calling at the same ports and their associated berths, other IEC voltage ratings may be considered. At the connection point, facing the socket/ship connection surface, the phase sequence shall be L1-L2-L3 or 1-2-3 or A-B-C or R-S-T, counterclockwise. A phase sequence indicator shall indicate the correct sequence before LVSC is energized or connected in parallel. When an observer looking at the phase sequence rotation diagram is fixed in place, the phases must rotate counterclockwise with respect to the fixed observer to produce a clockwise indication on the phase sequence indicator (Fig. 31).

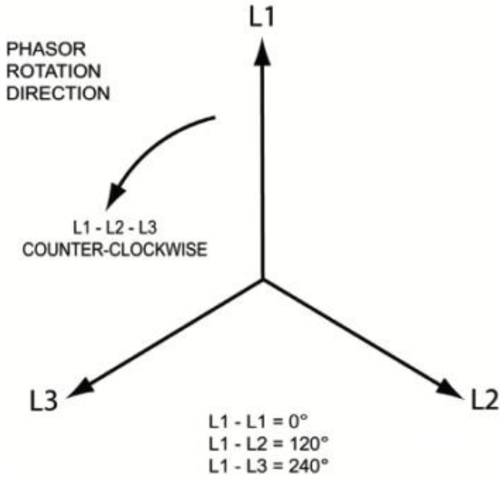


Fig.31. Phase sequence rotation – Positive direction

3.4 Power quality requirements for LVSC

Electrical marine equipment shall be connected only to shore supplies capable of meeting the voltage, frequency, and total harmonic distortion characteristics of the distribution system specified below. To meet the requirements, the compatibility assessment shall include verification of the following:

Voltage and frequency tolerances (continuous):

- Frequency shall not exceed continuous tolerances ±5% between no-load and rated power.
- For no-load conditions, the voltage at the point of shore connection shall not exceed a voltage rise of 6% of the rated voltage.
- For rated load conditions, the voltage at the point of shore connection shall not exceed a voltage drop of -3,5 % of the rated voltage.

Voltage and frequency transients:

The behavior of voltage and frequency at the shore connection under an appropriate range of load steps shall be defined and documented for each LV shore supply system. The maximum load step that can be expected when connected to a LV shore power supply shall be defined and documented for each vessel. The part of the system subject to the largest voltage dip or spike when the maximum load step is connected or disconnected shall be identified and verified that the voltage transient limits of +20 % and -15 % and the frequency transient limits of ±10 % are not exceeded.

Harmonic distortion:

Under no-load conditions, the voltage harmonic distortion limits shall not exceed 3% for the single harmonic and 5% for the total harmonic distortion. The above parameters shall be measured at the point of supply. Deviating voltage and frequency tolerances may be imposed by the owners or authorities responsible for the shore supply system and these shall be considered as part of the compatibility assessment to verify that the impact on the connected vessel load is acceptable. Where the potential loading conditions of a vessel when connected to a shore power supply LV would result in a different quality of supply to that specified above, due consideration shall be given to the effect this may have on the performance of the equipment.

3.5 Power System Protection

NEC 240.8 [29] is a safety requirement that prohibits the use of parallel fuses or circuit breakers unless they are factory assembled in parallel and listed as a unit. This statement does not apply in the case of the design of LVSC switching equipment because feeder breakers are not parallel inside the shore power switching equipment. The shore power switching equipment consists of a main and feeder circuit breaker, along with other control relays and interlock devices, tested at the factory to trip the main breaker when any feeder breaker is tripped. Such a design meets the safety intent of NEC 240.8 to act as one assembly, so long as the control interlock between the main breaker and the feeder breakers is tested at the LVSC switching equipment assembly site. The LVSC switching equipment consists of the manufacturer’s standard breakers equipped with internal factory-installed overcurrent and ground-fault protection devices. In addition, main breaker and feeder breakers are equipped with factory-installed and tested shunt trips, as shown in Fig. 32.

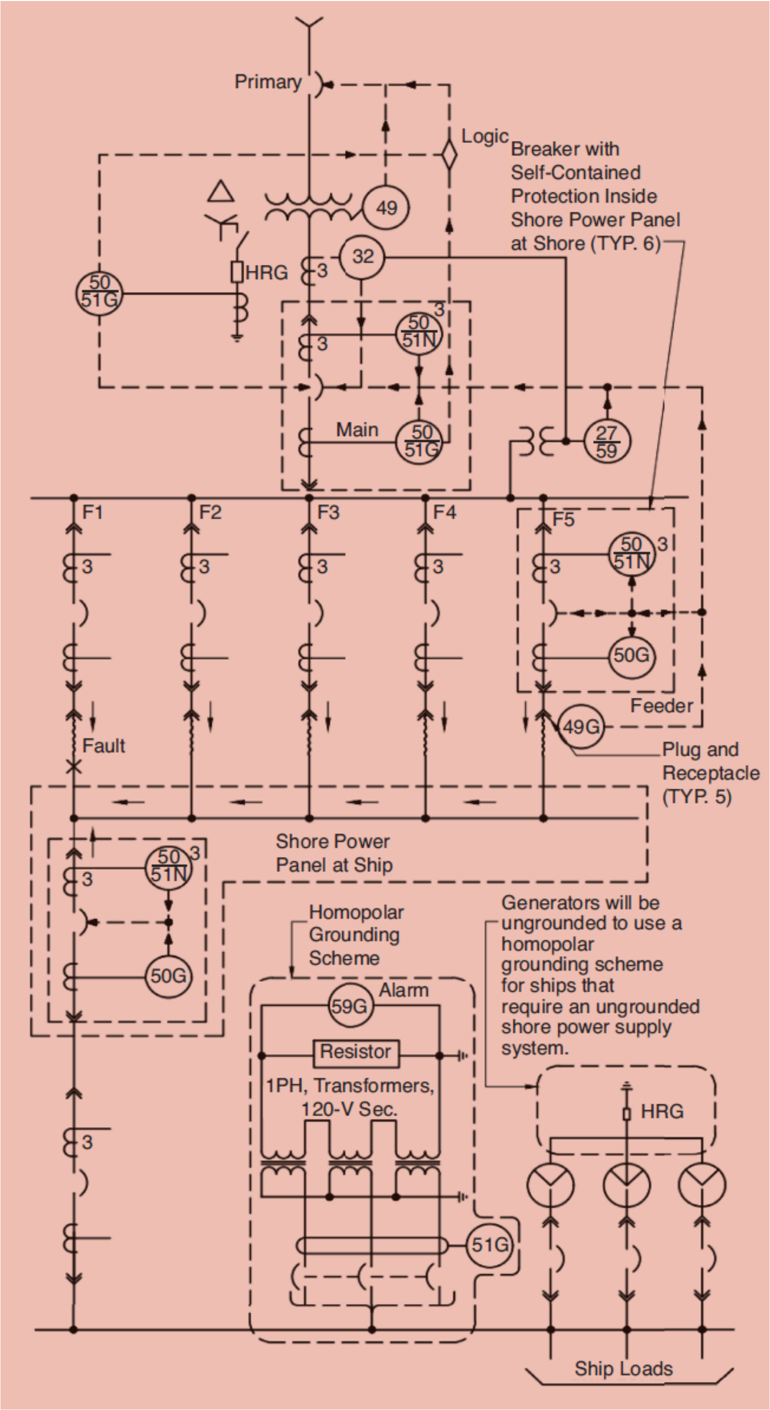


Fig. 32. A one-line diagram of a shore-to-ship power system protection scheme. The logic to trip the primary breaker is as follows: when the main breaker does not sense ground fault and the neutral relay senses ground fault, they provide a trip signal to the transformer primary breaker, as the fault is on the line side of the main breaker [13]. The operation as the ungrounded (IT) system follows this procedure: open the neutral disconnect switch and deactivate the automatic tripping scheme of the continuous monitoring of the neutral grounding resistor. The plug and receptacle assemblies are as follows: if a cable management system is used, there will be a second set of plugs and receptacle assemblies onboard the ship, as shown in [30]. TYP: typical; Sec: secondary.

Fig. 32 shows one such protection and breaker interlocks scheme between the main and feeder breakers. As the figure indicates, when any of the parallel feeder breakers is opened, the main circuit breaker opens simultaneously, without any intentional delay. The power system protection devices contained in the current draft standard are shown in this protection scheme using standard LV circuit breakers [31], [33], [35], [36]. Standard LV circuit breakers with integral built-in sensitive phase and ground fault current transformers can have communication capabilities that develop control interlock between the main and feeder breakers. The required electrical interlock between each feeder circuit breaker and the main circuit breaker can also be achieved by auxiliary relay contacts.

In addition, programmable relays can be used to provide this interlock and any other tripping contacts (such as from the safety loop schematic shown in Fig. 33) required to trip circuit breakers. The interlock between the main circuit breaker and the feeder circuit breakers can also be designed by changing the breaker trip circuit so that the main breaker will trip with input from the same protection devices that trip the feeder circuit breakers.

The conceptual protection scheme shown in Fig. 32 may vary somewhat among LV equipment suppliers' use of voltage relay instead of current relay for the HRG grounded power system and the sensitivity of the low-level ground-fault current. Equipment suppliers can also provide a combination of LV breakers and separate auxiliary relays for an interlock scheme. The real problem is that, without individual feeder breakers, all the sockets (receptacles) that are not needed for parallel feeders for smaller ships cannot be isolated from the shore power, posing a safety issue. The draft standard also includes a safety loop that shows feeder circuit breakers onshore. Feeder circuit breakers also comply with the NEC requirements to protect individual feeder cables and plug/receptacle assemblies from overload and short circuit ratings of the circuit components.

There are many other design schemes that can provide protection and interlock of the main breaker with feeder breakers. In any design plan, the LVSC shore-side equipment protection scheme needs to be completely wired and tested at the factory to ensure that a faulted feeder does not receive back feed from the parallel feeders by tripping the main breaker as soon as the faulted feeder breaker trips.

Table I shows the number of parallel feeders required to connect ships with different power demands at different supply voltages. Fig. 32 shows a fault on feeder F1 to illustrate how all parallel feeders can contribute to back feed the faulted location. Depending on the fault location, the fault current from the shore and the ship can add together during a synchronizing period. This possibility must be checked to confirm that plug/receptacle assemblies are protected so they do not exceed the short circuit current by more than 16 kA. As described in the draft standard, current-limiting devices may be required for LVSC power systems in larger ships. This is not shown in Figure 2 for simplicity, and power analysis is required before finalizing LVSC design.

TABLE I The parallel feeders for various ship power demands [30]

	Voltage (V)		
Power Demand kVA	**400**	**440**	**690**
Up to 250	2	1	1
251-500	3	2	2
501-750	4	3	2
751-1000	5	4	3

Mechanical Key Interlocks

Each plug/socket (plug/receptacle) assembly will have a mechanical interlock that will be released (when the plug/socket assembly is fully engaged) and go into the feeder breaker to close. On closing the feeder breaker, the key is released to go into the main breaker. The main breaker can have a selector switch to designate 1–5, indicating the number of feeder breakers required to close the main breaker. Each port will have its own written procedures and training for operators delineating safe cold-ironing operation. Test witnessing of the LVSC shore-side switching equipment will require factory mechanical interlock testing with the desired plug/socket assemblies and emergency trip interlocks shown in Fig. 33. To provide permissive logic before implementation of the synchronizing scheme that will close the ship circuit breaker (item 12 in Fig. 30), the ship switching equipment will require similar separate key interlocks with each plug/socket assembly on the ship.

Special Requirements for LVSC Equipment

All circuit breakers should be electrically operated, and the control voltage should implement a battery pack unit with a 30-min minimum rating. The LVSC equipment onshore should include space heaters, device 59 N, a transient voltage surge suppressor, three-phase voltage and a phase voltage sequence indicator, and an emergency switch (safety loop requirement). All breakers are to be equipped with contacts to trip by safety loop signals.

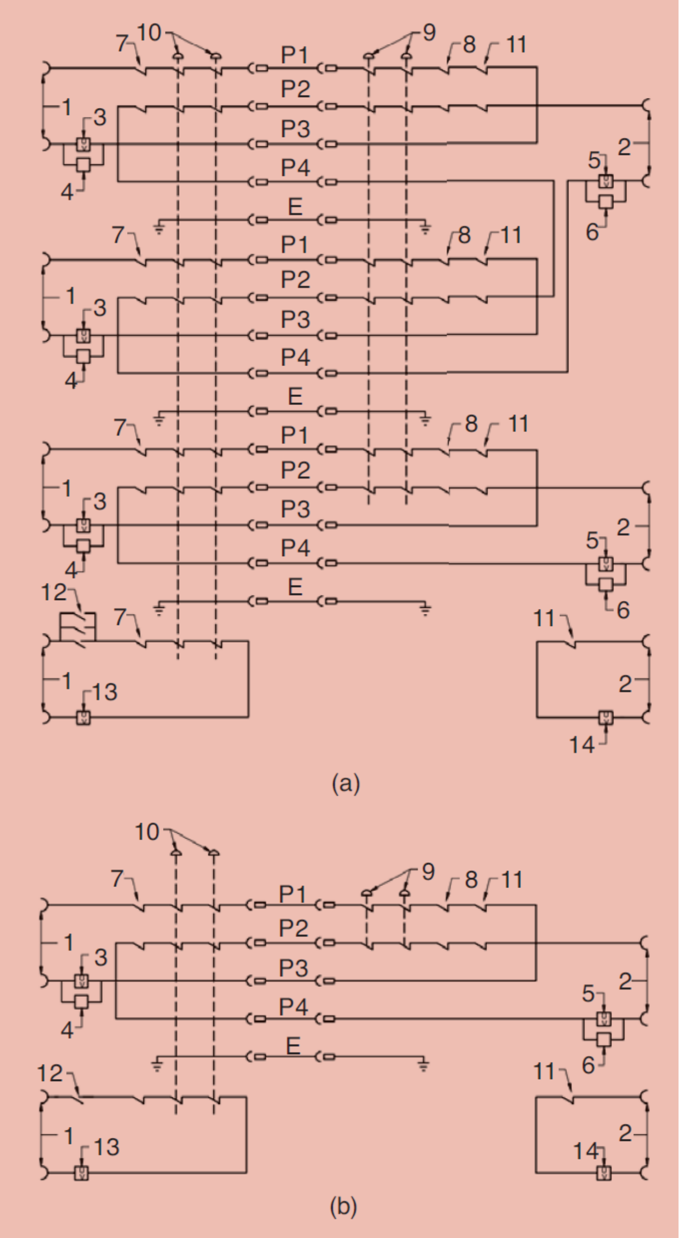


Fig. 33. A safety loop schematic [30]: (a) a circuit for three feeders and (b) a circuit for one feeder. 1) The control power pilot loop shore, 2) control power pilot loop ship, 3) feeder circuit breaker under the voltage coil (shore), 4) safety circuit coil on shore, 5) main circuit breaker under the voltage coil (ship), 6) safety circuit coil on the ship, 7) control emergency shutdown (ES) shore (including the shore-side main circuit breaker and feeder circuit breakers electrical trip), 8) control ES ship (including the onboard circuit breaker electrical trip), 9) manual ES ship (two shown), 10) manual ES shore (two shown), 11) trip from the ship safety loop circuit (see key 6), 12) trip from the shore-side feeder safety loop circuits (see key 4), 13) shore-side main circuit breaker under the voltage coil, and 14) onboard receiving switchboard circuit breaker under the voltage coil.

3.6 Ground-Fault Protection

HRG ground-fault protection using a 5A continuous neutral grounding resistor is recommended. This method of grounding a shore power substation transformer neutral employs a maximum resistor with a R value suitably defined to make an HRG system [32]. However, using a 5A continuous resistor is much more than what is required to make an HRG system when expected shore and ship combined system charging current is near 1 A. A 5A resistor is considered to be adequate for keeping phase-to-ground fault low with a sensitive ground-fault protection scheme. Neutral resistor R should be rated in amperes [28] to keep the following criteria applicable for different ship voltages:

$$R \le E_{LN}/I_C$$

where I_C is the total system charging current of the shore and the ship and is equal to $3I_{CO}$, where I_{CO} is each phase-to-ground system charging current under normal operation.

During the synchronizing period only, one generator with its neutral grounding will be in parallel with the shoreside HRG grounded system. During this period, ground fault at any location in the power system can split to go to two grounding locations, one at the shore transformer neutral and the other at the ship generator neutral. If the ship is equipped with a homopolar grounding scheme as shown in Fig. 32, then during the cold-ironing operation of such a system, the resistive component of the ground fault at any location can split and return to the source [37].

The two grounded power sources are in parallel. From a theoretical point of view, bolted phase-to-ground-fault current at the fault location will increase as both sources contribute to the fault current. This ground-fault current can be calculated by

$$I_{GF} = \sqrt{I_{Requivalent}^2 + I_C^2}$$

The value $I_{Requivalent}$ is the combined equivalent resistive component of the fault current derived using the following equation, where the shore power transformer neutral resistor and ship generator neutral resistor are R_{Shore} and R_{Ship}, respectively:

$$I_{Requivalent} = E_{LN}\frac{R_{Shore} + R_{Ship}}{R_{Shore}R_{Ship}}$$

The total capacitive component of the fault current I_C will split between shore and ship power sources as $I_{CGFShore}$ and $I_{CGFShip}$, respectively, resulting in fault currents from two power sources related as follows:

$$I_{GFShore} = \sqrt{I_{RShore}^2 + I_{CGFShore}^2}$$

and

$$I_{GFShip} = \sqrt{I_{RShip}^2 + I_{CGFShip}^2}$$

where

$$I_{CGFShore} = -3I_{COShore}$$
$$I_{RShore} = E_{LN}/R_{Shore}$$
$$I_{CGFShip} = -3I_{COShip}$$
$$I_{RShip} = E_{LN}/R_{Ship}$$

The value I_{CGF} represents the capacitive component of the phase–ground-fault current, which is at 180° to the system charging current ($3I_{CO}$) and is thus shown with a negative sign in above equations. E_{LN} is line-to-neutral voltage. The splitting of capacitance between the shore and the ship is not precise. Thus, these last equations are more theoretical, and it is more practical to use only the equations related to the resistive components. The expected phase–ground-fault currents indicated in Table II are based on a 5A shore transformer neutral grounding resistor and a 1A total (shore and ship) system charging current. The indicated 25% fault means that 25% of line-to-neutral voltage is considered as an internal fault to the shore power transformer at 25% away from neutral; the same applies to the 50% fault and the 75% fault. Bolted fault is assumed with zero fault impedance and a fault external to transformer.

TABLE II The expected ground-fault current [30]

Phase-ground fault type	Resistive component of fault current (A)	Capacitive component of fault current (A)	Total fault current (A)
Bolted fault	5.00	1.00	5.10
25% fault	3.75	0.75	3.83
50% fault	2.50	0.50	2.55
75% fault	1.25	0.25	1.28

Ships with ungrounded power systems connect to ungrounded shore power systems as indicated in the draft standard. Such ships are normally equipped with bus-connected homopolar grounding schemes [37] to detect ground faults by sounding an alarm without tripping onboard generators. Connecting such ships with ungrounded LVSC is not recommended because it can prove dangerous to maintenance personnel, as discussed above. If certain ships require an ungrounded shore power supply, as indicated in the draft standard, Annex D, then the best option is to have ships equipped with an isolation transformer but keep the shore power system grounded.

3.7 Safety Loop Circuit

The safety loop control schematic shown in Fig. 33 is a reproduction from the draft standard. It is based on using an onshore cable management reel. The safety loop control circuit voltage should not be more than 60 Vdc or 25 Vac based on safety requirements for touch potential. A conceptual schematic is shown using a double-loop control design, where the shore-side loop control voltage is independent of the ship-side loop control voltage. Thus, monitoring and control devices onshore and onboard the ship can be designed separately based on the control voltage available on each side.

The earth pin in each plug and socket assembly is used to route an equipotential bonding jumper between the shore and the ship grounding electrodes. Fig. 33 shows safety loop control schematics for three parallel feeders and a separate one for a single feeder. In the case of three feeders in parallel (Fig. 33a), two complete safety loops to control the schematics are shown. One upper loop involves the plug/sockets of two power supply feeders, whereas the second safety loop control schematic uses a single plug/socket assembly. The only difference in the choice of safety loop design is that a safety loop using two plug/socket assemblies would have approximately double the loop wire of the other safety loop. The choice of control voltage rating between ac and dc can affect which loop is the best design for voltage drop and capacitance coupling effects.

3.8 Power Plug and Socket

The power plugs and socket outlet shown in Fig. 34 are recommended for the LVSC between the shore and the ship. The standard requires the use of a mechanical securing device that locks the connection in the engaged position. The power plug/socket contacts sequence is as follows:

1) connection: earth contact, power contacts, pilot contacts
2) disconnection: pilot contacts, power contacts, earth contacts.

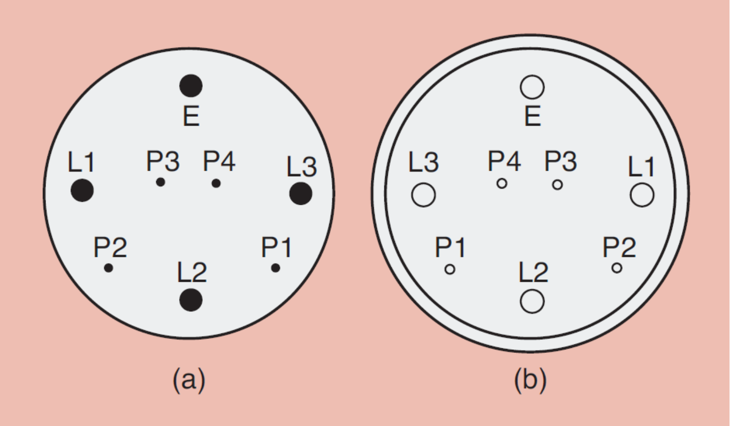


Fig. 34. The power plug and socket pin assignment [30]. (a) The plug/ship inlet face and (b) the socket-outlet/ship connector face. E: earth; L1: phase 1–A–R; L2: phase 2–B–S; P1: pilot 1; P2: pilot 2; P3: pilot 3; P4: pilot 4.

The plug, socket, ship's coupling and ship's input shall comply with IEC 60309-1 and IEC 60309-5 standards. The plug, receptacle, marine connector, and marine input assembly shall be provided with a mechanical locking device that locks the connection in the engaged position. One type of plug, socket, ship's input and ship's connector shall be used for all types of ships. Each outlet should be equipped with four pilot plugs. The maximum permissible short circuit current is 16 kA/1s and the maximum peak short circuit current is 40 kA.

3.9 Ship to shore interconnecting cables

The standard rated voltages of ship to shore connection cables are $U_0/U(U_m) = 0{,}6/1(1{,}2)kV\ r.m.s.$ where U_0 is the rated voltage between phase conductors and earth, U is the rated voltage between phase conductors and U_m is the maximum value of the highest system voltage that can be maintained under normal operating conditions at any time and at any point in the system.

The standard type of cable is 3 phases + Earth + 4 pilot wires. Cross section are typically 3x185 mm2. Cables shall be constructed as follows: three power cores and one or more grounding cores with copper conductors, insulation, and outer sheath. Lots shall be installed in the spaces between the power cores and the grounding core(s). The P1/P2 and P3/P4 conductors must be laid separately.

All conductors should be flexible (class 5 of IEC 60228). The conductors should be bare or metal-coated copper conductors. The cross-sectional area of the grounding conductors shall be at least 50% of the cross-sectional area of the power core conductors. Pilot conductors shall have a rated voltage of $U_0/U(U_m) = 150/250(300)V\ r.m.s.$ and minimum cross-sectional area of 1.5 mm2.

If an alternative to the recommendations is proposed, the facility may not be suitable for connection to a compliant shore supply/vessel. The use of an alternative should be documented and made available to the personnel responsible for compatibility testing.

3.10 Cable management system

The cable management system (CMS) must be capable of moving the ship-to-shore interconnecting cable so that the cable can pass between the outlet and the ship's entrance, while maintaining an optimum cable length that minimizes cable slack and prevents voltage limits from being exceeded. It should be equipped with a device (e.g. limit switch) independent of the control system to monitor maximum cable tension. The positioning of the CMS should prevent interference with vessel mooring and mooring systems, including those of vessels not connected to shore power while moored. The radius of the cables should be maintained above the manufacturer's recommended minimum bend radius during deployment, stationary operation and stowed condition. The CMS shall be capable of supporting the cables over the full range of vessel draft and tidal range and recovering and stowing the cables when the work is completed.

If the cable management system uses cable drum(s), the LVSC system rating shall be based on the operating condition with the maximum number of cable turns stowed on the drum encountered during normal operation. If applicable, the cable sizing shall include appropriate derating factors.

In LVSC systems, two connection configurations can be used: connection configuration with mobile CMS (Figure 35a) and connection configuration with fixed CMS (Figure 35b).

Detection of lack of available cable length and maximum cable tension limit should be done in two stages: Alarm and activation of emergency shutdown.

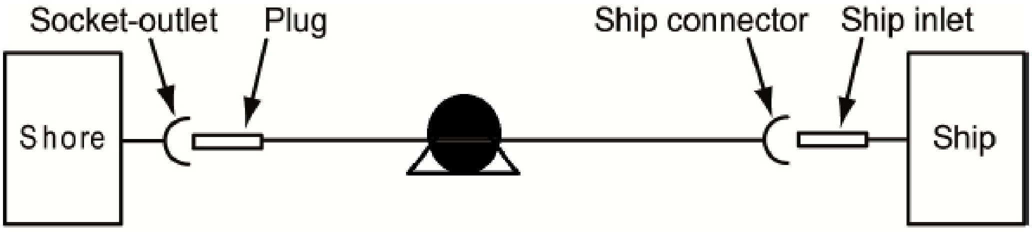


Fig. 35a. Connection configuration with mobile CMS

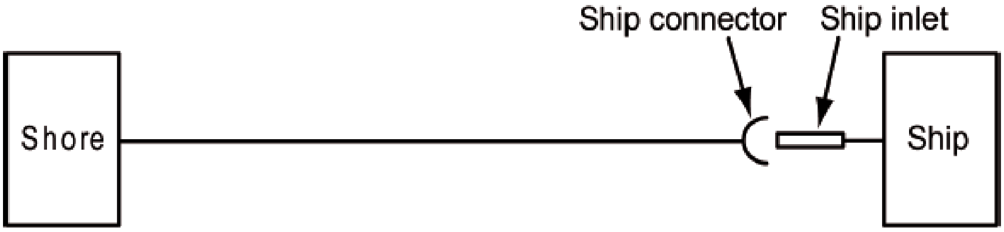


Fig. 35b. Connection configuration with fixed CMS

3.11 LVSC control and monitoring

Ship's equipment must be protected and controlled by the ship's own protection and control systems.

If shore supply fails for any reason, supply by ship's own generators is permissible after shore supply has been disconnected. Load transfer shall be by blackout or automatic synchronization. Synchronization shall be carried out on board.

Interlocking devices shall be provided so that shore power can only be connected to a decommissioned shipboard receiving switchboard. The interlocking devices shall be such as to prevent connection to an energized shipboard receiving switchboard in normal operation or in the event of a fault, e.g. a fault in the power failure monitoring circuit. Simultaneous connection of a LV shore supply and a shipboard power source to the same de-energized section of the electrical system shall be prevented.

LV -Shore power and ship power source(s) must be temporarily connected in parallel in accordance with the following:

- The load shall be automatically synchronized, the synchronization shall have a timeout function, and the load shall be transferred between the shore power supply LV and the ship power source(s) after they are connected in parallel.
- The load transfer shall be completed in the shortest practicable time without causing failure of machinery or equipment or tripping of protective devices, and this time shall be the basis for establishing the transfer time limit.
- Any system or function used for shore connection paralleling or control shall have no effect on the ship's electrical system when no shore connection is available.

The transmission time limit shall be defined and made available to responsible personnel. If the transfer time limit is adjustable to match the ability of an external power source to absorb and deliver load, the procedure for setting this limit shall be addressed in the operating instructions. Where the operation of only a specific or limited number of ship power sources is required to enable the safe transfer of loads between a LV shore power supply and ship power sources, the arrangements shall meet this requirement before and during parallel connection.

If the specified time limit for the transfer of load between LV -shore supply and ship's power source(s) is exceeded, one of the sources shall be automatically disconnected from the ship and an alarm shall be raised to inform the appropriate service personnel. Special care shall be taken not to exceed the maximum permissible load levels of the gensets (see IEC 60092-301). If load reductions are required to shift the load, this shall not result in a loss of services essential to the safety of the ship.

3.12 General operating procedure diagram

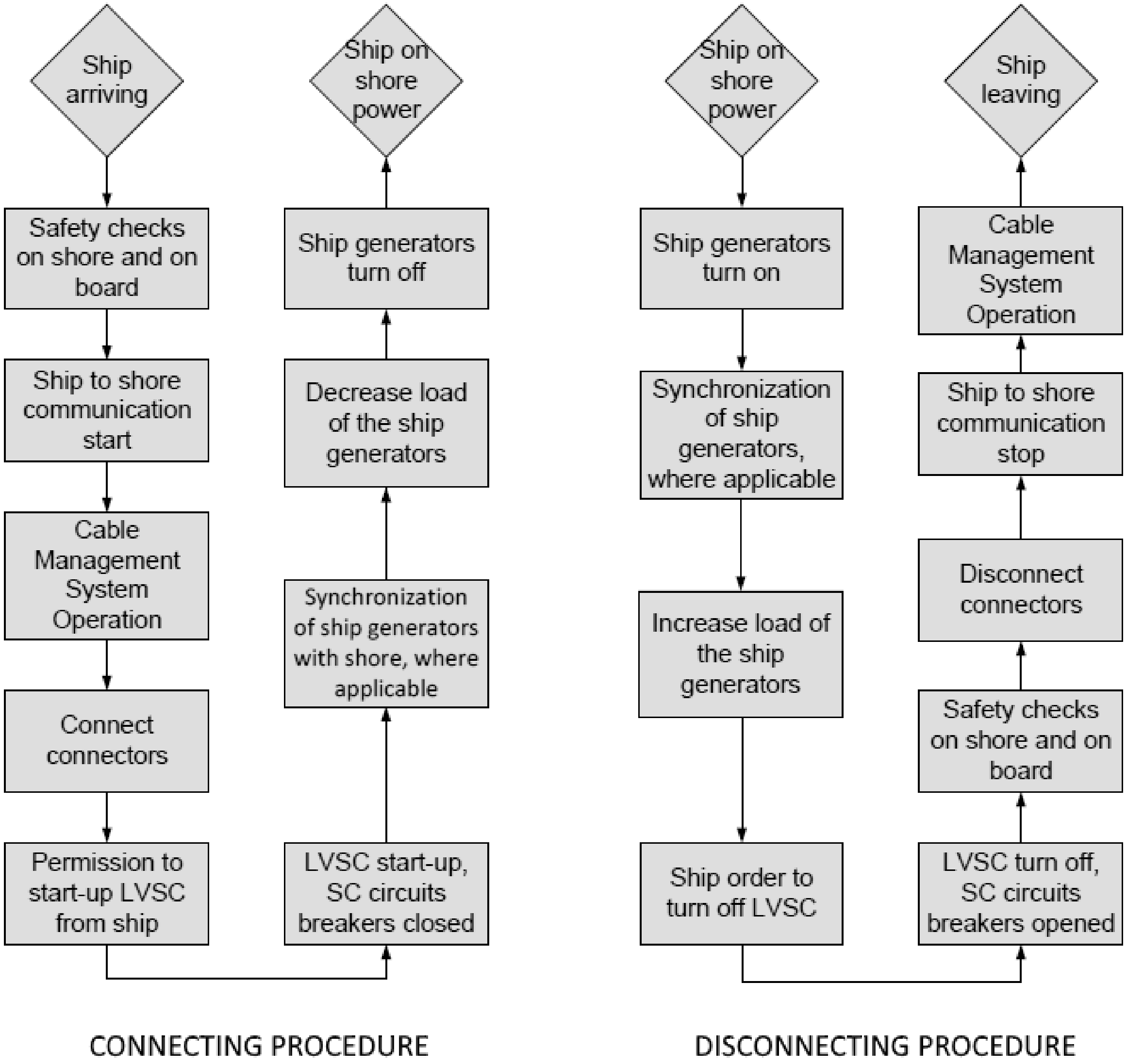


Fig. 36. Connection and disconnection procedures

3.13 Documentation

For the LVSC system and each control device, the manufacturer shall provide documentation on the operation, technical data, installation instructions, required commissioning, troubleshooting, maintenance and repair, as well as a list of required test equipment and replaceable parts.

A complete system description, including schematics, indicating set points and operating instructions, shall be prepared by the parties responsible for the shore and ship LVSC systems. The parties responsible for shore and ship LVSC systems shall provide a test and verification program for the entire installation demonstrating compliance with the specification.

3.14 Some final recommendations from draft Standard IEEE/IEC 80005-3

The following conclusions and recommendations can be drawn.

1) The design of LVSC equipment onshore can be a switchboard or switchgear. LVSC shore-side switching equipment with a main breaker interlocked with feeder breakers can be designed to meet the technical requirements included in the draft standard. All protection and interlocks should be tested at the factory to assure that the main breaker trips when any of the feeder breakers trip.

2) The authority having jurisdiction over approval of port LVSC design requires that shore power be interrupted by the main breaker when any of the feeder breakers trips under fault condition without intentional delay. It is recommended that the port authority and the professional engineer involved in the LVSC design, as shown in the draft standard and discussed in this article, should work as a team to obtain approval from the AHJ to ensure that shore power feeder breakers never see fault current split as the main breaker trips. This meets the technical intent of the requirements listed in NEC 240.8 that all parallel breakers or fuses should be listed as one unit.

3) Ships with ungrounded power systems will consist of a homopolar grounding device [37] and remain in operation when the ship is connected to shore power. Such ships requiring ungrounded shore power supply connection have an option to use an HRG grounded shore power system and request shore not to trip the shore power on phase–ground-fault condition, as there is no issue of transient overvoltage (the system is HRG grounded) and the fault current is low and within the safe limits of 30 V or lower. The resistive component of the fault current on ship (if the fault occurs on ship) will increase slightly but should be acceptable to the ship authority. If a port refuses to agree not to trip the shore power on phase–ground-fault condition and the ship authority does not accept the increased resistive component of fault condition at the ship, then a grounding expert technical report should be considered to devise an acceptable design solution between the port and ship authority.

4) While the existing draft Standard IEEE/IEC 80005-3 define requirements and protections of standard plug-in connections required for cold ironing, the standards for battery charging equipment and its integration still do not officially exist. As can be seen from the results of the research carried out in Work Package 4, future electric and hybrid ships will require new solutions and topologies of shore connections, characterized by the increased use of power electronics devices, the integration of energy storage and environmentally friendly renewable sources, and the use of DC distribution systems. Accordingly, there is a need to extend existing standards or develop new ones that incorporate these solutions, with the ultimate aim of enabling an easier transition to greener solutions for ferry and RO -RO transport.

4. SHORE-TO-SHIP POWER AND BATTERIES UTILIZATION IN MARITIME RULES & STANDARDS

4.1 Codes and Standards regarding battery installations onboard ships

The present chapter provides an overview of current applicable regulations, guidelines and standards for the use of batteries and shore connection in shipping.

International environmental, security and safety standards for shipping are developed by United Nation dedicated agency named *"International Maritime Organization"* (IMO). The work of IMO is conducted through five committees:

1. Maritime Safety Committee (MSC)
2. Marine Environment Protection Committee (MEPC)
3. Legal Committee
4. Technical Cooperation Committee, to help developing countries improve their ability to comply with international rules and standards;
5. Facilitation Committee, to simplify the documentation and formalities required in international shipping.

The regulation of batteries usage in ships does not yet appear to be on the agenda of IMO or its committees, and the only reference to this technology is made into the *International Maritime Dangerous Goods Code (IMDG Code)*, which covers batteries as dangerous goods when packed as cargo. In many cases, safety and technical requirements for a battery installation are established by *IMO 1455 - Guidelines for the approval of alternatives and equivalents* as provided for in various IMO instruments. This is particularly the case in the absence of applicable or relevant Class rules or Flag state requirements. Table III lists some key international rules. So far, it appears that most of the development work has been done by specific Flag States and Class Societies, which therefore will be our focus in next paragraphs.

In addition to that, many other organizations typically develop rules and standards to cover safety and test requirements of electric systems and stationary power systems, such as the International Electrotechnical Commission (IEC), Underwriter's Laboratory (UL) and the International Organization for Standardization (ISO). Applicable IEC standards for battery installations in general applications ships are depicted in Table IV, while relevant standards for specific maritime battery applications or battery technologies are shown in Table V.

TABLE III Key international rules (IMO) [38]

International rules (IMO)	**Year of publication**	**Short description**
MARPOL Annex VI	2005	Prevention of Air Pollution from Ships - Sets limits on sulphur oxide and nitrogen oxide emissions from ship exhausts and prohibits deliberate emissions of ozone depleting substances; designated emission control areas set more stringent standards for SOx, NOx and particulate matter. - A chapter adopted in 2011 covers mandatory technical and operational energy efficiency measures aimed at reducing greenhouse gas emissions from ships (IMO, 2019).

SOLAS		The International Convention for the Safety of Life at Sea (SOLAS) - Defines as an international agreed minimum requirement for the construction, equipment and operation of ships. Flag States must ensure that these minimum requirements are met. - Chapter II-1 - Construction - Subdivision and stability, machinery and electrical installations, specifies amongst other things the requirements for generators for electrical power generation. - The IMO subcommittee on Fire Protection (FP) has agreed to introduce new requirements for electrical equipment and wiring, ventilation and gas detection, and these requirements entered into force on 1st January 2016.
MSC.1Circ.1455	2013	Guidelines for the approval of alternatives and equivalents as provided for in various IMO instruments - intended for application when approving alternative and/or equivalency designs in general and specifically according to the provisions given for alternative design and arrangements in applicable statutory IMO instruments. - serve to outline the methodology for the analysis and approval process for which the approval of an alternative and/or equivalent design is sought.
IMDG Code		International Maritime Dangerous Goods Code - Covers dangerous goods as packed cargo. - Does not include use of dangerous goods in the ship’s own cargo tanks (as could be the interpretation for batteries used as “fuel” is not included.

TABLE IV Relevant standards for battery installation [38]

Standard	**Year of publication**	**Short description**
IEC 62619	2017	Secondary cells and batteries containing alkaline or other non-acid electrolytes
IEC 62620 (2014-12-01)	2014	Secondary cells and batteries containing alkaline or other non-acid electrolytes - Secondary lithium cells and batteries for use in industrial applications Edition: 1.0
UN Manual of Tests and Criteria, UN DOT 38.3	2015	Transport of Dangerous Goods
IEC 62281 Edition: 2.0 (2014-02-01)	2014	Safety of primary and secondary lithium cells and batteries during transport
UL1642 Edition 5 (2012-03-13)	2012	Standard for Lithium Batteries
UL1973		Standard for Batteries for Use in Light Electric Rail (LER) Applications and Stationary Applications
UL 9540	2016	Standard for Energy Storage Systems and Equipment
IEC 60529 Edition: 2.2 (2013-10-01)	2013	Degrees of protection provided by enclosures (IP Code)
IEC 61508	2010	Functional safety of electrical/electronic/programmable electronic safety-related systems – Part 0: Functional safety

Edition: 1.0 (2010)		- Relevant for Battery Management System (BMS)
IEC 60092-504 Edition: 3.0 (2001-03-22)	2001	Electrical installations in ships - Part 504: Special features - Control and instrumentation - Relevant for BMS
IEC 62061 Edition: 1.0 (2010-08-01)		Guidance on the application of ISO 13849-1 and IEC 62061 in the design of safety-related control systems for machinery - Relevant for BMS

TABLE V Relevant standards for specific maritime battery applications or battery technologies [38]

Standards / Rule	**Year of publication**	**Short description**
EN 50110 Edition 2.N (2013-06-01)	2013	Operation of electrical installations -- Part 1: General requirements - Supporting documentation for batteries and electrical testing
IEC 61508 Edition: 1.0 (2005-01-20)	2005	Functional safety of electrical/electronic/programmable electronic safety-related systems - Supporting documentation for batteries and electrical testing
IEC 61511 Edition: 1.0 (2003-12-19)	2003	Functional safety - Safety instrumented systems for the process industry sector - Supporting documentation for batteries and electrical testing
ISO 26262 Edition: 1 (2011-11-14)	2001	Road vehicles -- Functional safety - Supporting documentation for batteries and electrical testing
IEEE 45-2002	2002	Recommended Practice for Electrical Installations on Shipboard

4.2 Flag States guidelines on batteries usage in shipping

While most nations do not have any stated requirements in place, some national authorities released specific guidelines on maritime battery systems to fill the regulation gap and to cope with the increasing number of partial/full electric vessels navigating in their regions (TABLE VI).

TABLE VI Overview of most important Flag States' guidelines [38]

Flag State Authority	**Year**	**Guideline**	**Link**
Norwegian Maritime Authority	2016	Guidelines for chemical energy storage - maritime battery systems	Link
Danish Maritime Authority	-	Battery operation of ships	Link
U.S. Maritime Administration (MARAD)	2016	Maritime Environmental and Technical Assistance (META) Program - Battery risk assessment study. MARAD partnered with Foss Maritime to conduct a battery risk assessment study for their hybrid tugs.	Link
U.K. Maritime and Coastguard Agency	2016	Electrical Installations - Guidance for Safe Design, Installation and Operation of Lithium-ion Batteries	Link

4.3 Marine Classification Societies

Classification societies are non-governmental organizations that set up, maintain, survey and certify technical standards for construction and operation of ships, leveraging on accumulation of maritime knowledge and technology to safeguard maritime safety and pollution prevention. The certification of compliance provided by classification societies on behalf of authorizing flag states is mandatory for a ship owner to be able to register its ship and to obtain a marine insurance.

According to UK P&I Club [39] there are more than 40 organizations worldwide that includes marine classification as one of their activities, out of which only 12 are official members of the IACS – International Association of Classification Societies [40]. IACS is a non-governmental organization funded in 1968 to secure as much uniformity as possible in the application of standards, providing forums for discussion and development of Unified Requirements and Unified Interpretations, which are then adopted and applied by each IACS member society [41].

The following TABLE VII summarizes rules and guidelines on battery and shore connection utilization given by the five Class Societies member of IACS covering most of the European fleet:

TABLE VII Overview of applicable Class requirements for battery installations and their status

Class Society	Date	Type	Title	Link
ABS	2020	Guideline	**Hybrid electric power systems for marine and Offshore applications** - Dedicated to the application of hybrid electric power systems	Link
	2020	Guideline	**Use of lithium batteries in the marine and Offshore industries** - Provides class requirements and reference standards to facilitate effective installation and operation of lithium battery systems.	Link
	2011	Guideline	**High Voltage Shore Connection**	Link
BV	2020	Rules	**Rules for Classification of Ships:** Pt F, Ch 11, Sec 21 – Battery system Pt F, Ch 11, Sec 22 – Electric Hybrid Pt F, Ch 11, Sec 29 – Electric Hybrid Prepared	Link
	2010	Rule Notes	**RN557 -** High-Voltage Shore Connection System	Link
DNV GL	2020	Rules	**Rules and Standards for classification: Ships (RU-SHIP)** Pt. 6 Ch.2 Sec.1 - Electrical Energy Storage	Link
	2020	Rules	**Rules and Standards for classification: Ships (RU-SHIP)** Pt.6 Ch. 7 Sec. 5 - Electrical shore connections - Shore power	Link
LR	2020	Rules	**Rules and Regulations for the Classification of Ships** Pt 6, Ch 2, 12 - Batteries	Link
	2020	Rules	**Rules and Regulations for the Classification of Ships** Pt 7, Ch 13 – On-shore Power Supplies	Link

	2016	Guideline	**Battery installations -** Key hazards to consider and Lloyd's Register's approach to approval	Link
RINA	2019	Rules	**Rules for the Classification of Ships** Pt C, Ch 2, App 2 – Battery powered ships Pt F, Ch 13, Sec 2 – Hybrid Propulsion Ship (HYB-…)	Link
	2009	Rules	**Rules for the Classification of Ships** Pt C, Ch 2, App 2 **-** High Voltage Shore Connection (HVSC)	Link

For the purpose of this paper, we will provide an overview of rules and regulations on the topic provided by DNV GL which, according to the Maritime Battery Forum, in 2021 is the Classification Societies counting the highest market share in the battery equipped fleet.

4.4 Overview on DNV GL rules covering shore-to-ship power and batteries utilization

4.4.1 Class Notations

With reference to *"DNV GL Rules and Standards for classification: Ships (RU-SHIP)"* [42] as of April 2021, ships are assignees of "Class Notations", meaning abbreviations or keywords expressing a specific feature relating to a Vessel or its machinery, systems and equipment, or service area. Class Notations are assigned to a Vessel in order to determine applicable requirements in the Rules for assignment and/or retention of that Class Notation.

Class Notations classified as follows:

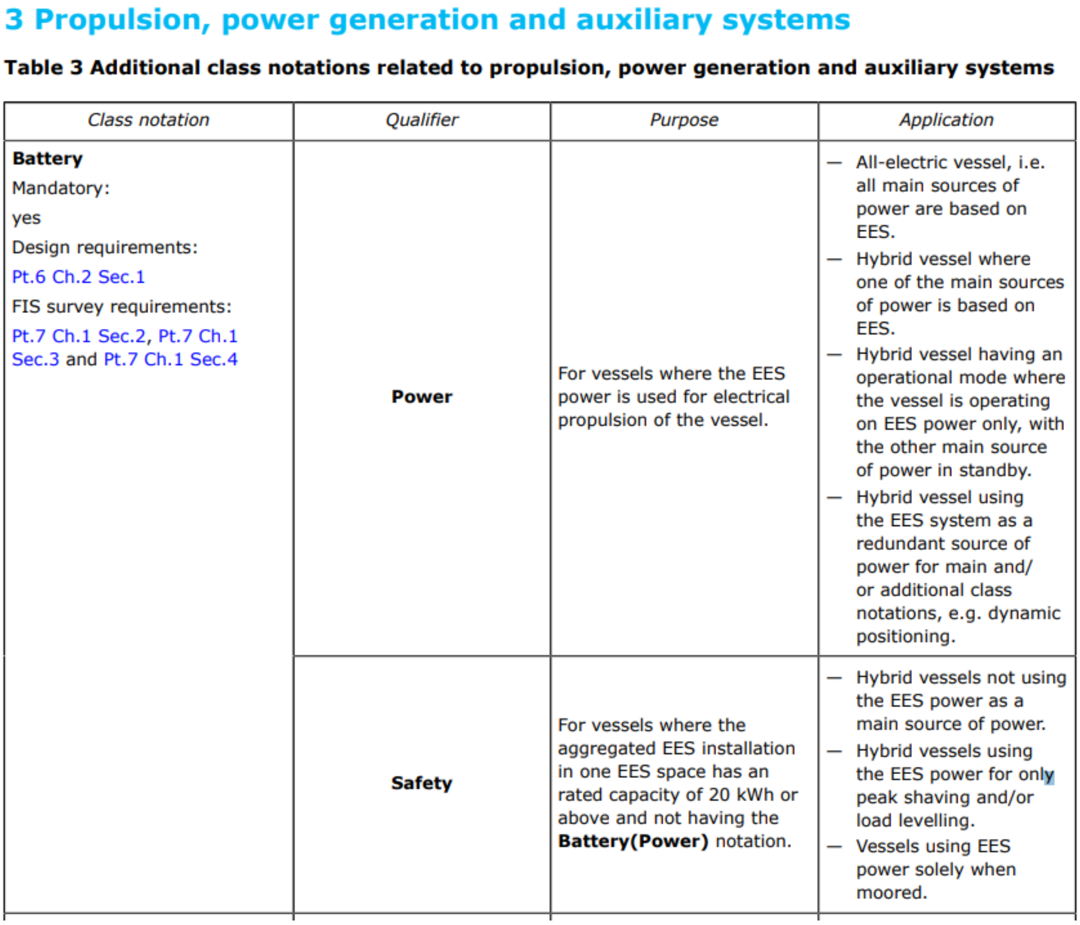
- Main Class Notation
- Ship type notations
    - mandatory ship type notations
    - optional ship type notations
- Additional Class Notations
    - mandatory additional notations
    - optional additional notations
- Service area restriction

Main Class Notation and mandatory Class Notation stipulates requirements for:

- availability of Main Functions and the safety of installations supporting the Main Functions;
- structural strength and integrity of essential parts of the vessel's hull and its appendages;
- the safety of machinery, systems and equipment supporting non- Main Functions that constitute possible hazards to personnel and vessel.

Optional Class Notations include requirements to safety levels and availability beyond that of Main Class and mandatory Class Notations.

In *Pt. 1 Ch.2 Sec. 4 – "Additional Class Notation"*, mention is made to both batteries' utilization onboard and shore-to-ship power. The applicable Class Notations are respectively "Battery (Power)", "Battery (Safety)" and "Shore Power". These Class Notations are all mandatory and their scope and applicability is summarized in following tables:

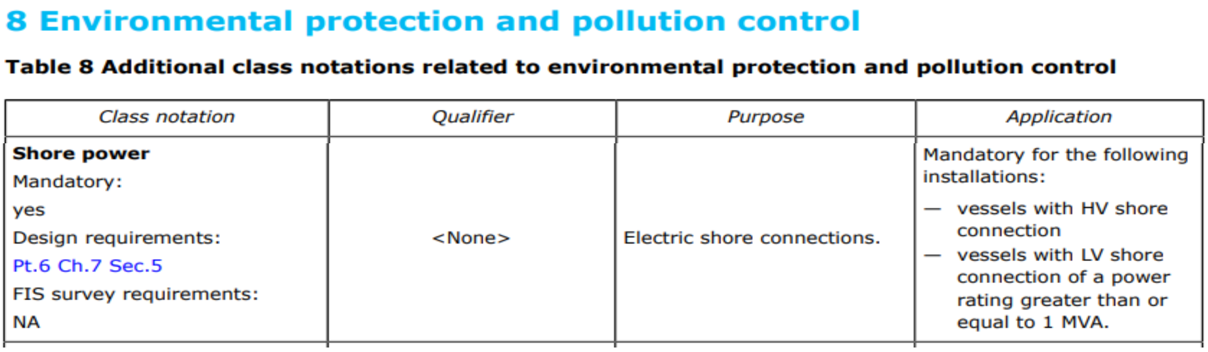


3 Propulsion, power generation and auxiliary systems

Table 3 Additional class notations related to propulsion, power generation and auxiliary systems

Class notation	*Qualifier*	*Purpose*	*Application*
Battery Mandatory: yes Design requirements: Pt.6 Ch.2 Sec.1 FIS survey requirements: Pt.7 Ch.1 Sec.2, Pt.7 Ch.1 Sec.3 and Pt.7 Ch.1 Sec.4	**Power**	For vessels where the EES power is used for electrical propulsion of the vessel.	— All-electric vessel, i.e. all main sources of power are based on EES. — Hybrid vessel where one of the main sources of power is based on EES. — Hybrid vessel having an operational mode where the vessel is operating on EES power only, with the other main source of power in standby. — Hybrid vessel using the EES system as a redundant source of power for main and/ or additional class notations, e.g. dynamic positioning.
	Safety	For vessels where the aggregated EES installation in one EES space has an rated capacity of 20 kWh or above and not having the **Battery(Power)** notation.	— Hybrid vessels not using the EES power as a main source of power. — Hybrid vessels using the EES power for only peak shaving and/or load levelling. — Vessels using EES power solely when moored.

Fig. 37. Overall indications on DNV GL “Battery” Class Notation



8 Environmental protection and pollution control

Table 8 Additional class notations related to environmental protection and pollution control

Class notation	*Qualifier*	*Purpose*	*Application*
Shore power Mandatory: yes Design requirements: Pt.6 Ch.7 Sec.5 FIS survey requirements: NA	<None>	Electric shore connections.	Mandatory for the following installations: — vessels with HV shore connection — vessels with LV shore connection of a power rating greater than or equal to 1 MVA.

Fig. 38. Overall indications on DNV GL “Shore Power” Class Notation

4.4.2 “Battery” Class Notation

The additional class notation Battery sets requirement for safety and availability of EES installations onboard vessels. In particular, *“Pt. 6 Ch.2 Sec.1 - Electrical Energy Storage”* covers design, installation and certification requirements for lithium-ion battery systems and electrochemical capacitor systems.

The Class Notation Battery(Safety) is dedicated to those vessels using EES only as integration of main power producers – i.e. for peak shaving and/or load levelling purpose or utilized when moored only. The related requirements are based on the design principle that any single failure in the EES system shall not render any main functions unavailable for more than the maximum restoration time subjected to class approval.

The Class Notation Battery(Power) represents a stricter version of the Battery(Safety), since it is addressed to vessels where all the main sources of power are based on EES only. This implies that, on top of fulfilling all requirements already needed for Class notation Battery(Safety), the main sources of power shall consist of at least two independent EES systems located in two separate EES spaces, with local operation panel and additional requirements related to:

- EES capacity
- Energy Management System
- Equipment testing

For this Class Notation, also Operating Instruction and Maintenance Plan for EES shall include additional procedures on top of those mainly related to fire safety already requested for Class notation Battery(Safety). The additional procedures to be introduced into operating instruction are:

- charging procedure
- normal operation procedures of the EES system
- local operation procedure
- conditions and procedures to prepare the EES system for extended period of standby.

At the same time, the maintenance plan to be kept onboard shall include verification procedures for batteries State Of Health (SOH) on top of systematic maintenance and function testing details required by Battery(Safety).

For those cases in which batteries are used as a part of the dynamic positioning systems, above Class Notations’ requirements must be integrated with what prescribed by following Class Notations:

- Dynamic positioning systems – **DYNPOS** and **DPS**
- Dynamic positioning systems with enhanced reliability – **DYNPOS (E, ER)**

in *“Pt. 6 Ch.3 – Navigation, manoeuvring and position keeping”*.

To conclude the overview on prescriptions given by DNVGL on batteries utilization on board, it is to be mentioned that, from a lifecycle point of view, surveys for Battery Class Notation can be included in the annual or the renewal survey following requirements indicated in Pt.7 Ch.1 Sec.2 and Sec. 4.

4.4.3 "Shore Power" Class Notation

DNV GL dedicates a whole set of rules to electrical shore connections in *"Pt.6 Ch. 7 Sec. 5* - *Electrical shore connections* - *Shore power"* where can be found a list of requirements to be compliant with for a transfer of power utilizing an electrical shore connection while in port. As previously mentioned, this Class Notation is mandatory for vessels with high voltage shore connection and low voltage shore connection with power rating greater than or equal to 1 MVA.

The rules cover the design of electrical shore connections, the ship side installation of necessary equipment and the verification of the installations, while they explicitly exclude:

- The compatibility between the vessel and the shore side installation for each port the vessel will be berthing at;
- The evaluation of the criticality in case of loss of power supply, due to the utility systems onshore;
- The usage of shore connections during service and maintenance docking (the requirements for those shore connections are covered by *Pt.4 Ch.8*).

The system design comprises the following aspects:

- system functionality of the electrical shore connection as a total system. In addition, requirements to circuit breakers, earthing switches and protective functions are given;
- control systems and control system interface between the shore and the vessel. Requirements are given for necessary functionality. Generally, control and monitoring systems shall comply with relevant parts of *Pt.4 Ch.9*. Physical installations on shore are not covered by these rules;
- ship side electrical equipment and installations. However, only specific requirements related to electrical shore connections are given. Generally, equipment and installations shall comply with relevant parts of *Pt.4 Ch.8*.

The requirements in this section are generally based on applicable standards for ships as issued by International Electrotechnical Commission (IEC) and in particular to the IEC/IEEE 80005-series. Where reference is made to such standard, it is the edition of the standard in force at the time of contract between builder and owner that shall be applied.

4.5 Battery safety and safety assessment

This part of the document provides an analysis of key aspects of battery safety, focusing on lithium-ion batteries (which are the most used ones for modern transportation applications). The assessment is structured to analyse and provide guidance through the effects and characteristics of risk that arise from the multitude of different potential battery configurations, technical approaches, and technologies that exist in the market – including installation alongside a fuel cell. A safety assessment approach, based on the Hazard Identification (HAZID) methodology, is also presented, to help in evaluating the risks involved in battery use onboard ships.

4.5.1 Fundamental aspects of lithium-ion battery safety

Safety concerns with regard to lithium-ion batteries come from two sources – one is the presence of flammable, unstable electrolyte, and the second is the presence of metal electrodes that can burn and often release oxygen. Ignition and likelihood of a safety event is largely linked to the flammable electrolyte, while the high temperature and difficult to extinguish nature of the fire is largely linked to the second aspect. Based on these components, there are two primary failure modes or effects that can result from lithium-ion battery abuse: cascading thermal runaway and the release of toxic and flammable gasses.

Thermal runaway

Thermal runaway is the exothermic reaction that occurs when a lithium-ion battery starts to burn. The thermal event often starts from an abuse mechanism that causes sufficient internal temperature rise to ignite the electrolyte within a given cell. This fire then poses significant risk of igniting the metallic electrodes that are contained within the battery cell, thus producing a high temperature metal (Class D) fire. Additionally, these metals may contain oxygen, which is thus released as it burns. Not all lithium-ion batteries contain oxygen within the electrodes but all lithium-ion batteries on the market today contain electrolyte that can ignite and cause this thermal runaway scenario.

A maritime battery system is typically made up of thousands of cells. Thus, the failure and total heat release of a single cell is a relatively minor threat. The greater threat comes from that thermal event producing sufficient heat that it propagates to other cells, causing them to go into thermal runaway. As this cascade through the battery, heat produced increases exponentially and the risk is developed of a fire in which the entire battery is involved. Thus, battery modules and systems must be engineered to protect against propagation based on the cell that is used, and these cascading protections are the key feature with regard to system design for safety.

Electrolyte off gas

The electrolyte that is contained within a given cell consists of an organic solvent, typically variants of ethyl carbonates. This means that they are flammable, and additionally, this means the gasses that are produced during a failure scenario are also flammable and can present an explosion risk. These gasses also typically contain other species which are toxic – such as HCl and HF. These aspects of battery offgas thus require consideration with regard to ignition sources and ventilation within both the battery module and battery room.

Battery Technology considerations

In addition to general safety aspects of lithium-ion batteries, there can also be significant differences between specific systems. These variations consist of the chemistry of the battery cells themselves, the design of the module (assembly of multiple battery cells) and the controls system internal to the battery, commonly called the Battery Management System (BMS).

BATTERY MANAGEMENT SYSTEM – BMS **-** The battery is only as strong as its weakest link (cell). All batteries within the system will degrade at slightly different rates. A quality BMS system will be best able to minimize those variations as it keeps batteries in balance. In addition, the BMS is responsible for calculating current limits, SOC, and State of Health (SOH). These are all complex functions that require years of experience and in-depth knowledge of the specific battery system. A high quality BMS system is a key component of a safe and fully effective battery system. The BMS is also vital in preventing the converter overcharging the battery system. Such failures may cause more than one cell or module to fail simultaneously. Note that the most probable scenario for such failures is that any fire or off-gassing will start at the weakest cell or module, before spreading to the rest of the system.

BATTERY CELL AND CHEMISTRY CONSIDERATIONS **-** As stated previously, any lithium-ion battery will burn as it is an energy source. A battery system is built up of tens of thousands of cells. Thus, some of the key factors with regard to safety then are making sure in the case that one battery fails in some sort of thermal event that others around it do not do the same. A key aspect of this then is how much heat is produced by the cell. A larger cell will contain a larger amount of energy and thus produce more heat when it burns. Larger cells produce advantages with regard to energy content and density of a system but system design must be sure to take into account this larger size. Chemistry is also a factor. The majority of lithium-ion batteries in use are of a Lithium Cobalt Oxide (LCO), Nickel Cobalt Manganese (NCM) or Lithium Manganese Oxide (LMO) type. These chemistries present similarities in terms of having layered metal oxides and thus producing oxygen during thermal runaway events. Thus, these chemistries will tend to burn more violently and with greater amount of heat released. Iron Phosphate (LFP) batteries, on the other hand, do not contain oxygen in the internal metal structures and thus do not produce as much heat in the case of a thermal failure. Additionally, Lithium Titanate Oxide (LTO) batteries will tend to produce less heat during a thermal failure scenario.

MODULE DESIGN **-** There are many different lithium-ion systems that can all be made to be safe. A key aspect of safety is ensuring safe design of the battery packaging. A module is a collection of batteries that forms the modular basis for the battery system. Thus, it is imperative that a battery module is designed specific to the battery system it encases. The battery module is also the level at which key detections are made – multiple sensors for voltage, temperature, and current will be placed in the module. The higher number of sensors, the better the visibility the control system has into the battery and thus the ability to detect an event as soon as possible. Many systems have voltage sensors on every cell, which is highly advantageous. Many will also have multiple temperature sensors placed strategically, as well as current sensors. An increased amount of sensors will typically accompany increased system cost. Battery packaging or module will also contain the systems responsible for thermal management of the battery. Batteries are typically either air-cooled or liquid cooled. Which one is necessary will depend on the battery cell as well as the duty cycle – or how hard it is being used? However, a more capable cooling system will help ensure more even operation and degradation of the battery cells. This is important because as even just one or two cells begin to die within a battery system, the capability of the whole system will likely be limited.

Operational safety risks of lithium-ion batteries

The following are the primary ways in which a lithium-ion battery can be misused or abused in such a way that is at high risk of producing a safety event as described in the preceding sections. Many of these risks come from undesired electrical operation, and thus the control system – Battery Management System, BMS – plays a key role with regard to safety, as well as electrical architecture and electrical system protections. These factors are described as they pertain to a cell, but if electrical protections are insufficient, the risk posed by these abuse mechanisms increases exponentially when applied to a full module or even worse, a full rack.

OVERCHARGE - Overcharging a lithium-ion battery represents one of the highest likelihoods and highest consequences scenarios that can occur. Overcharging a battery means charging it to a point where its voltage is greater than it is rated to be at. When a battery is overcharged, internal temperature rises and the electrolyte is at significant risk of breaking down into gaseous constituents. Both of these lead to risk of igniting the electrolyte in liquid or gaseous form. Incorrect communication of SOC from the BMS to the converter or the Power Management System, imbalance between cells, or even a short circuit producing an excessive charge current are all scenarios which may pose a risk of overcharge. Voltage limits will vary at the cell level depending on battery chemistry.

OVERDISCHARGE - Similar to overcharge, overdischarge represents a scenario where the battery voltage has dropped below manufacturer recommended limits. This can lead to decomposition of the electrodes within the battery which then poses a risk of short circuiting – and thus of heating electrolyte and causing a fire. Also similar to overcharge, the BMS has a prime role in protecting against overdischarge. Voltage limits will vary at the cell level depending on battery chemistry.

OVERCURRENT - Overcurrent comes from charging or discharging the battery at a power level that is too high. This can cause excessive temperature generation thus leading to electrolyte ignition. In addition, this can lead to incorrect voltage management, and thus accidental overcharging or overdischarging. The converter connected to the battery should be equipped with an overcurrent protection, where the limits are set by the BMS. In severe cases, the excessive current may be of a fault or short circuit type, and thus out of control; thus, passive electrical protections such as fuses and breakers are the key to prevent this failure.

OVERHEATING - Thermal management of a battery system is the key. Excessive temperatures will drive degradation and can also lead to a safety event. If ambient temperature is too high, then the battery may operate in a way that further increases its internal temperature beyond acceptable limits. Acceptable upper temperature limits are often near 45°C.

EXCESSIVE COLD - Operating a battery in temperatures below its rated range will increase internal resistance, decrease efficiency and can also lead to a safety event through lithium plating on the anode or formation of dendrites – thus resulting in an internal short circuit and rapid heating of the electrolyte. Lower temperature thresholds range widely between different cell chemistries, and manufacturer recommendations should be followed closely, but it can be considered generally inadvisable to operate below 10°C.

EXTERNAL SHORT CIRCUIT - An external short circuit is likely a familiar concept and poses the same risk as many other failure modes described in this section. If the battery is rapidly charged or discharged, the electrolyte in a cell may heat to the point of ignition and pose a threat of thermal runaway and/or flammable or toxic off-gas release. As mentioned before, passive electrical protections such as fuses, and breakers are the key to prevent this failure.

MECHANICAL DAMAGE - Mechanical damage may result from external protrusion into the battery room under collision, errant crane operation, or perhaps in the case of explosion or other mistakes. If a cell is mechanically damaged, a risk is posed of the electrodes coming into contact and short circuiting as well as many other electrical components. This short-circuiting thus produces the same failure mode of heating the electrolyte to the point of ignition.

EXTERNAL FIRE - An external fire poses the threat of involving the battery system and thus direct overheating and combustion of all battery materials. An external fire might also heat up the battery space, such that the ambient temperature exceeds the acceptable limit of safe battery operation. Proper fire segregation of the battery rom and a fire extinguishing system that removes the heat from the battery space is then important.

INTERNAL DEFECT - An internal defect represents perhaps the largest threat to a lithium-ion battery system because it is something that cannot be detected by the battery BMS. Most all other failures will result in indications from voltage or temperature sensors that will be detected and accounted for by the BMS. An internal defect may produce an internal short with little to no warning. This is the result of issues or quality control from manufacturing. Although many cell producers maintain a high degree of quality control, the large number of cells required for an installation and the inability to detect, make an internal defect a significant risk and the main reason that off-gas and thermal runaway must be considered and protected against in even the most highly controlled and monitored systems.

4.5.2 Safety assessment approach

This section describes the objective and a methodology usable for the safety assessment of batteries installation onboard a ship. *It is relevant to notice that the use of the proposed methodology is not an obligation, but it is only one of the possible approaches that can be used to evaluate the safety of onboard batteries installation.*

Objectives

The objective of the safety assessment is to identify key risks posed to the battery system as they pertain to various installation arrangements and technologies. The approach here proposed can be used to evaluate how conceivable design variations in the maritime battery system affect the safety on board a vessel.

The approach/methodology

The risk assessment can be carried out on the basis of the following HAZID methodology.

HAZARD IDENTIFICATION

In general, a HAZID is a structured approach based on documents and drawings, as basis to identifying risks and hazards involved with operation or the use of equipment and/or systems. The key objectives of a HAZID are:

- To identify hazards and hazardous events that may give rise to serious and immediate risk to personnel, environment, and assets;
- To identify causes and consequences of hazardous events;
- To identify preventive and mitigating measures (e.g. measures to prevent the hazardous events from occurring and engineering or operational controls to help prevent escalation) that are already included in design for managing the risks associated with the identified hazards;
- To assess risks semi-quantitatively by using a risk matrix; and
- To recommend any potential new measures to be implemented in design and/or during operation.

The relationship between the hazard, hazardous event, causes, consequences and preventive and mitigating measures is illustrated in Fig. 39.

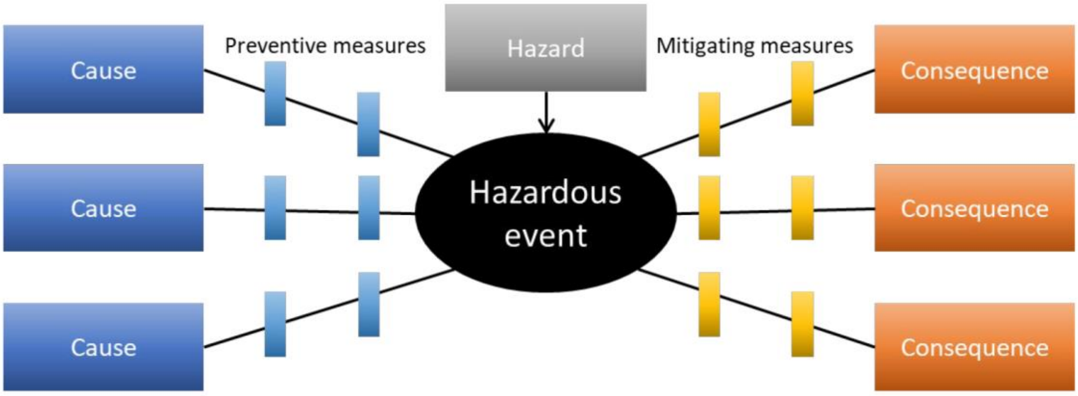


Fig. 39. Illustration of the relationship between the hazard, hazardous events, causes, consequences, preventive and mitigation measures. [38]

A graphical representation of a HAZID process is illustrated in Fig. 40, while its main steps are described in more detail below.

1. The first step of the HAZID is to identify HAZID nodes to assess the specifics of each individual area or operation.
2. The second step is to identify the hazards corresponding to each node.
3. For each hazard the potential causes along with the potential consequence is to be identified.
4. For each hazard, safeguards are identified. What measures can prevent an incident from happening, as well as measures intended to control development of the hazard or mitigating the consequence of the hazard.

5. The risk ranking step involve the categorization of the identified hazards. It is not the estimation of their associated risks. For each hazard the severity and likelihood are decided and based on the decision the risk of the hazard is determined.
6. If the preventive or mitigating measures (safeguards) are identified to be insufficient to manage the hazard, or that further assessments are required to obtain a better understanding of the hazard, recommendations should be raised and assigned to one of the evaluating parties to have the responsibility to follow up and make sure the recommendation is taken further.

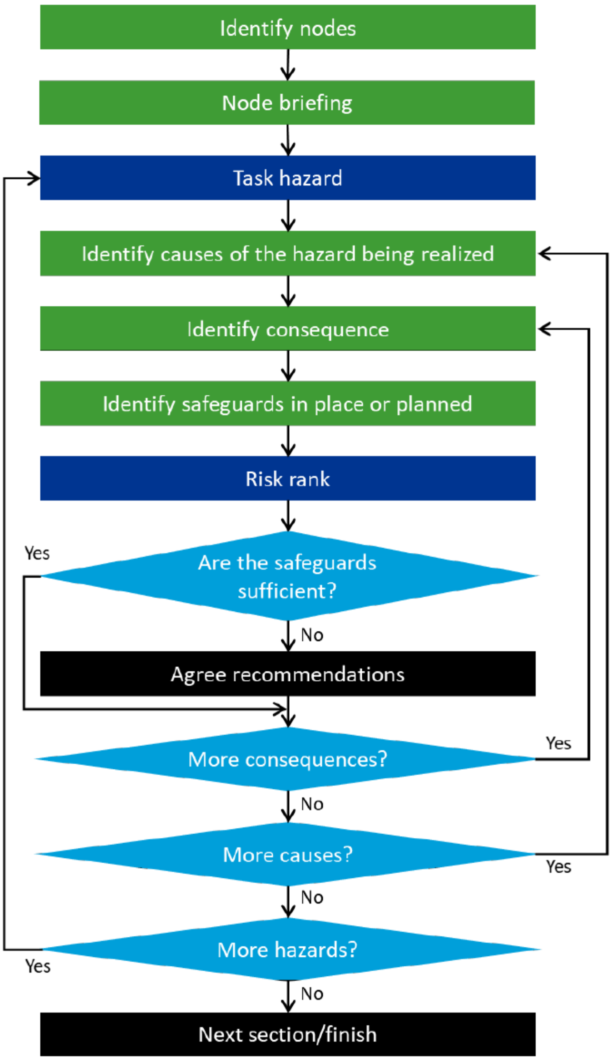


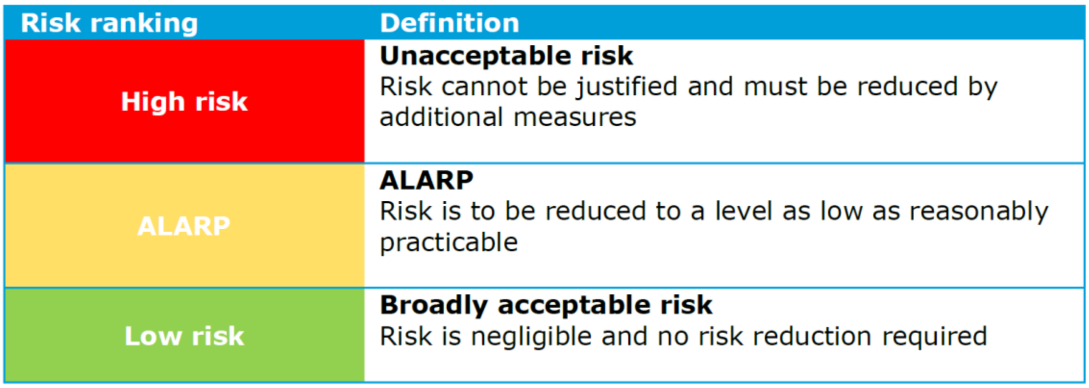
Fig. 40 HAZID procedure [38]

RISK RANKING

The risk related to a hazardous event is a function of the frequency if the event and the severity of its potential consequences. To determine the risk of the hazardous events, the frequency and severity of each hazardous event must be evaluated and decided. As the risk is established as the combination of a given consequence and the likelihood of an event, this enables the ranking of the hazardous events in a risk matrix. In the risk matrix, the hazardous events are classified as low, ALARP (as low as reasonably practicable) and high risk, as defined in TABLE VIII and illustrated in Fig. 40. The definition of consequences severity index and likelihood index are shown in TABLE IX and X.

For this safety assessment, the proposed risk matrix (Fig. 40) is based on DNV GL Recommended Practice DNV-RPA203. It should be noted that there is no universal definition of risk, but the risk needs to be defined by the analysts and accepted by the project or program management. The definitions differ widely between different application sectors. In this approach, the focus of the risk ranking is been on safety and environment protection.

TABLE VIII Classifications of risk used in the risk matrix. [38]



Risk ranking	Definition
High risk	**Unacceptable risk** Risk cannot be justified and must be reduced by additional measures
ALARP	**ALARP** Risk is to be reduced to a level as low as reasonably practicable
Low risk	**Broadly acceptable risk** Risk is negligible and no risk reduction required

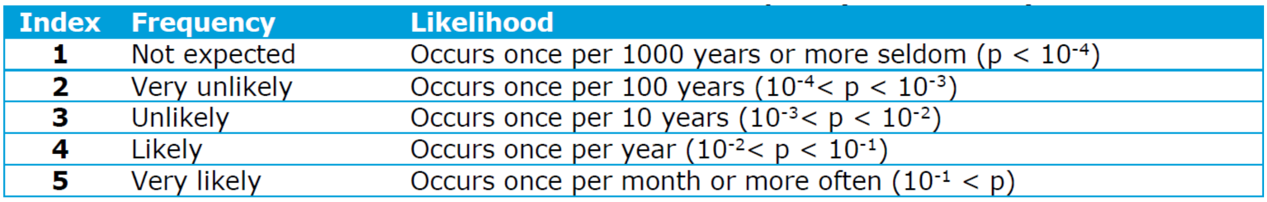
Consequence \ Likelihood		1 Not expected	2 Very unlikely	3 Unlikely	4 Likely	5 Very likely
1	No effect	🟩	🟩	🟩	🟨	🟨
2	Minor effect	🟩	🟩	🟨	🟨	🟨
3	Moderate effect	🟩	🟨	🟨	🟨	🟥
4	Major effect	🟨	🟨	🟨	🟥	🟥
5	Hazardous effect	🟨	🟨	🟥	🟥	🟥

Fig. 41 Risk matrix for the safety assessment. [38]

TABLE IX Severity index used for the evaluation of consequence in the safety assessment. [38]

Index	**Consequence**	**People**	**Environment**	**Asset**	**Downtime of system**	**Reputation**
1	No effect	No or superficial injuries	Slight effect	Slight damage	< 2 hours	Slight impact; local public awareness, but no public concern
2	Minor effect	Slight injury, a few lost work days	Minor effect	Minor damage	< 1 day	Limited impact; local public concern may include media
3	Moderate effect	Major injury, long term absence	Localized effect	Localized damage	1 – 10 days	Considerable impact; regional public/slight national media attention
4	Major effect	Single fatality or permanent disability	Major effect	Major damage	10 – 60 days	National impact and public concern; Mobilized of action groups
5	Hazardous effect	Multiple fatalities	Massive effect damage over large area	Extensive damage	>60 days	Extensive negative attention in international media

TABLE X Likelihood index used for the evaluation of frequency in the safety assessment. [38]



Index	**Frequency**	**Likelihood**
1	Not expected	Occurs once per 1000 years or more seldom ($p < 10^{-4}$)
2	Very unlikely	Occurs once per 100 years ($10^{-4} < p < 10^{-3}$)
3	Unlikely	Occurs once per 10 years ($10^{-3} < p < 10^{-2}$)
4	Likely	Occurs once per year ($10^{-2} < p < 10^{-1}$)
5	Very likely	Occurs once per month or more often ($10^{-1} < p$)

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