Università degli Studi di Trieste
Archivio della ricerca – postprint

Shore-to-Ship Power

This paper presents the requirements and technologies for providing ship power from a shore connection when the ship is in port. This requirement is increasingly driven by the environmental consideration of reducing emission from the ship power generation when in port.

By Giorgio Sulligoi, *Senior Member IEEE*, Daniele Bosich, *Member IEEE*,
Roberto Pelaschiar, Gennaro Lipardi, and Fabio Tosato

ABSTRACT | This contribution starts with a review of the state of the art of existing high-voltage shore connection (HVSC) systems in terms of principles, rules, publications, technologies, and relevant installations. Then, tutorial sections present the main technical aspects of HVSC systems as ship-to-shore interface, shore equipment (transformers, converters, etc.), onboard devices (cubicles, shore switchboard, etc.), operating sequences, and feasibility aspects, for both commercial and military applications. Finally, some technical challenges are presented, concerning intentional/unintentional bonding, interactions between HVSC bonding and cathodic protection systems, bonding opportunity, and electrical safety aspects related to bonding issues in case of large earth fault currents in port facilities.

KEYWORDS | All electric ship; cold ironing; cruise vessel; earth fault currents; electric safety; high-voltage shore connection (HVSC); naval vessel; port earthing systems; ship–shore bonding; touch voltage

I. INTRODUCTION

The global strategies for the exploitation of natural resources push toward reducing the environmental impact and improving the efficiency of the present and future energy solutions. In the maritime sector, many ship owners and ports are beginning to consider the "green ship" concept, which can be described in several technological aspects. From the owner's viewpoint, high efficiency motors, electrical propulsion, variable speed drives, storage systems, low power light systems, new materials for hull construction and painting, etc., are among the solutions 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 is responsible for almost 90% of the global shipped goods, and there are estimations which foresee to triple the present volumes of shipped goods, due to the rapid development of Asian markets [1].

When a ship is at berth, both at the pier or in the port bay, it utilizes onboard electric generators to supply power for shipboard technical and hotel services. For the time when the ship remains in the port area, she is responsible for relevant emissions of polluting agents such 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 become the first source of air pollution [2].

For the time when large ships are docked at a pier, a technique called the high-voltage shore connection (HVSC) system (also referred to as "cold ironing" or "alternate marine power") is often used for locally eliminating emissions [3]. Conventionally employed at low-voltage (LV) levels, it has recently become available also for high-voltage (HV) systems (mainly voltages in the range 1–11 kV), thus making it possible to supply multimegawatt electric power to large berthed ships (an HVSC is normally intended for electrical power exceeding 1 MW to be supplied) [4]. The technique foresees to switch off the shipboard electrical generators for the whole berthing period, and to provide electrical power for ship services from the land, using a dedicated cable line. It is assumed that electrical 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. There is also a

---

Manuscript accepted October 13, 2015.

G. Sulligoi, **D. Bosich**, and **F. Tosato** are with the Department of Engineering and Architecture, University of Trieste, Trieste 34127, Italy (e-mail: gsulligoi@units.it; dbosich@units.it; tosato@units.it).
R. Pelaschiar is with the Electrical Power Automation and Safety Systems Office, Fincantieri Italian Shipyards, Trieste 34123, Italy (e-mail: roberto.pelaschiar@fincantieri.it).
G. Lipardi is with the Electrical Plants & Naval Automation Office of Naval Directorate, Italian Navy, Rome 00196, Italy (e-mail: gennaro.lipardi@marina.difesa.it).

European Union (EU) Commission Recommendation that foresees the total or partial reduction of taxes on the electrical power delivered to ships using shore connections, thus making them more attractive to owners [5].

As for HVSC, only a few ports in the world are endowed with adequate infrastructure. However, existing realizations already prove the technical feasibility of HVSC for almost all types of ships of interest, regardless of the difference in voltage or frequency levels between land and shipboard electrical power systems.

More than technical issues, currently a practical obstacle to the development of the HVSC systems is the lack of approved law regulations. Instead, from the technical point of view, a technical standardization effort is represented by the joint International Electrotechnical Commission (IEC), International Organization for Standardization (ISO), and IEEE working group, which has created Standard 80005-1 between 2008 and 2012 [6].

Other obstacles to overcome in order to develop HVSC systems are: limited port distribution system capacity (in both power and voltage levels); limited port power supply line capacity (in both power and voltage levels); room availability to install HVSC dedicated cables, sockets, switchboards, converters, and transformers; and the need for upgrading a shipboard power management system (PMS) to parallel the ship to the land grid and to avoid blackouts (especially for passenger ships). A relevant attention is certainly given to small ports or single pier stations, formerly fed the medium voltage (i.e., in the range 10–60 kV), to improve power supply line voltage levels to HV ones (i.e., at voltages exceeding 100 kV). This creates problems of augmented earth fault currents, so the port earthing system needs be redesigned, along with the need of assuring additional multimegawatt generating capacity from the land power system.

II. STATE OF THE ART

The possibility for ships at the pier to switch off onboard generators is becoming more and more interesting for many reasons. Environmental restrictions, incentives, the maturation of standard practices, and the recently made available standard [6] are factors that could cause an extended use of HVSC. Rules, incentive policies, maritime zone restrictions, and sustainability conditions to build new port areas or to refit disused port areas could be key factors in developing HVSC systems. At the moment, less impact is observed from economic incentives on delivered energy or from other technical–economical motivations. HVSC systems appear to be successful where they become an "enabling" technology, rather than simply a "more convenient" technology (owners in particular do not seem to be ready to assume economical risks on a pure technological basis). For instance, at the moment, in some ports in Italy, the environmental impact evaluation (VIA) procedure led by the Ministry of Environment has requested the electrification of the new piers for some city ports where high levels of air pollution caused by stopping ships have already been ascertained: in these cases, either reinfrastructuring is made more sustainable, or new port infrastructure will not be authorized. The IEC/ISO/IEEE Standard 80005-1 [6] is currently the first technical reference, and it briefly covers the following topics (it applies neither to the LVSC system nor to dry-dock recovering of the ships):

- the HV pier distribution system;
- the connection and interface (from the shore to the 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 technological state of the art of an HVSC installation is described in [6], whereas the following sections explain the viewpoint of the two most important players: the ship manufacturer of a large civilian vessel and the Navy.

III. SHIP MANUFACTURER'S POINT OF VIEW ON HVSC FOR LARGE CRUISE VESSELS

A. General Aspects

When docked in a port, a large cruise vessel requires power of about 8–12 MW to manage various onboard services [7]. Such power is normally generated by one of the main diesel generators, which then produces SOx, NOx, CO_2, and particulate matter. The quantity of emission during an 8-h (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 auxiliary engines to stop during port operation.

Since 2001, cruise companies started providing their cruise vessels with facilities to provide power to the ship from HV shore power. Today, many ports are fully operative to supply power to vessels from local HV grids: Los Angeles (USA), Seattle (USA), Juneau (USA), San Francisco (USA), Long Beach (USA), San Diego (USA), Vancouver (Canada), and Halifax (Canada).

B. HVSC on Large All-Electric Cruise Vessels

The typical electric integrated power system (IPS) of an all-electric cruise liner [7] 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 vessels or 6.6 kV for smaller vessels. Such voltage levels are required for electrical distribution, as onboard power station size can

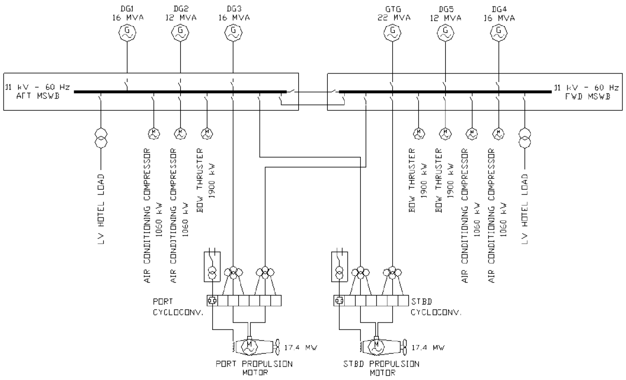


Fig. 1. ***IPS of an all-electric cruise liner.***

Fig. 3. ***Typical switchboard for shore connection purposes.***

be higher than 65 MW in a large vessel. The main switchboard supplies power to the main users such as the propulsion system, bow and stern thruster electric motors, air conditioning compressor electric motors, MV/LV transformers feeding engine room substations, accommodations services, and galleys.

The frequency of the generating system on a passenger vessel is typically 60 Hz. This allows an easy shore connection of a 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 this, as already indicated above, a modern all-electric cruise liner at pier normally needs 8–12 MW (which is the size of a single generator (Fig. 1), corresponding to the pier operation power demand [7]), the frequency converters will satisfy such power demand and, at the same time, will provide enough short circuit current for correct intervention of electrical protection relays installed on the ship electrical plant.

For the physical connection of a ship to the shore line, a dedicated HV switchboard power cubicle with special sockets is installed onboard the vessel. The typical switchboard for shore connection purposes with a closeup of shore power supply cable 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 of the following equipment:

- the shore connection cubicle breaker (CB “A”), installed in the 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 communication between the ship and the shore side substation.

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

Fig. 7 shows the one line diagram of the HVSC plant defined by the IEC/ISO/IEEE standard [6] in which the shore side distribution transformer star points connected to the ship hull through a neutral resistor with a dedicated neutral line. This arrangement is needed because, on a

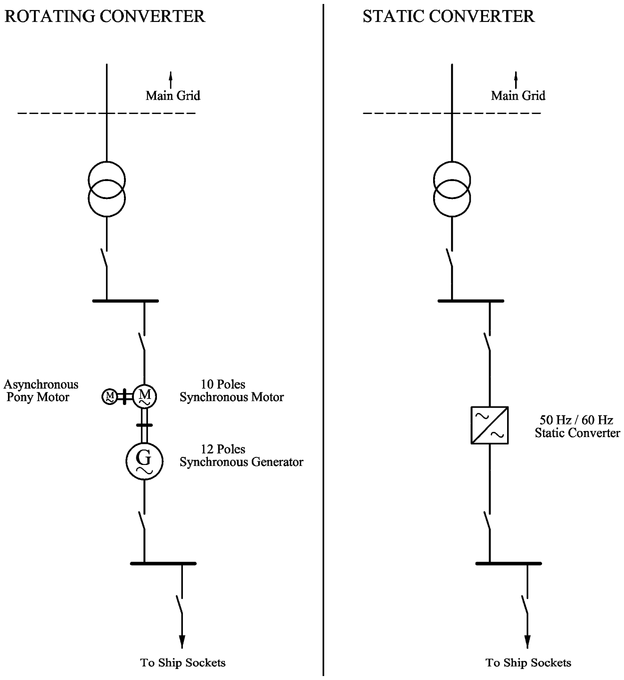


Fig. 2. ***Use of static or rotating converters.***

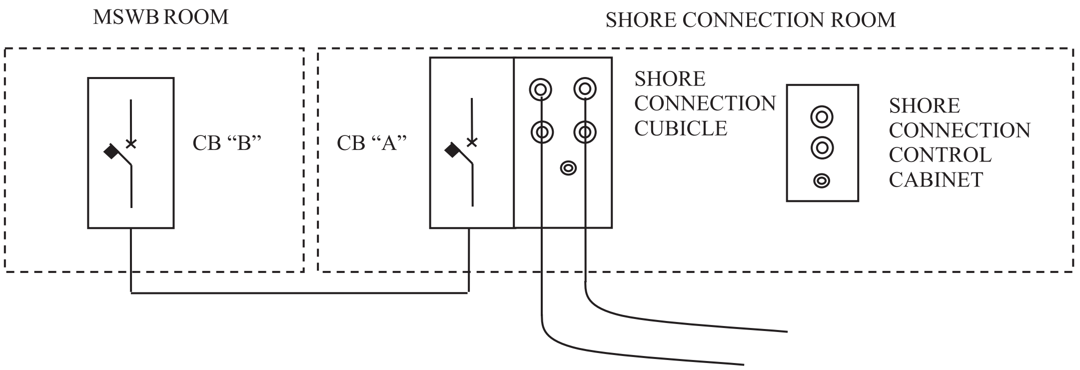


Fig. 4. *Simple block diagram of the typical ship side plant.*

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 the vessel's shore operation, the same protection principle is maintained. The IEC/ISO/IEEE standard also requires an equipotential bonding between the ship's hull and the 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's shore connection is to be immediately shut down and a restoration of power through 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 power and earth contacts on power sockets installed on the HVSC cubicle.

C. HVSC Sequence on Large All-Electric Cruise Vessels

When a ship is alongside a quay and physically connected to the shoreline, 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's automation system. The operator can remotely control the whole operation from a workstation located in the engine control room (ECR), which is the space normally manned during various ship operations.

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

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

Fig. 5. *Shore connection control cabinet.*

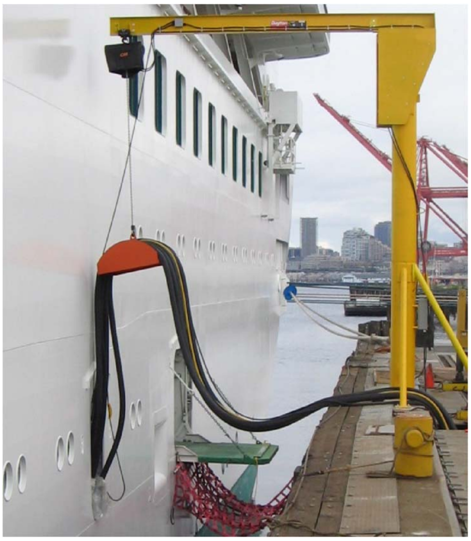
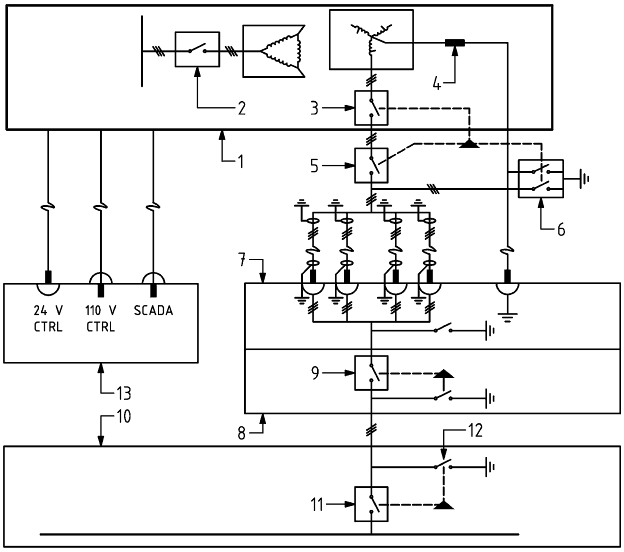


Fig. 6. *Dedicated crane.*



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 HVSC plant [6].***

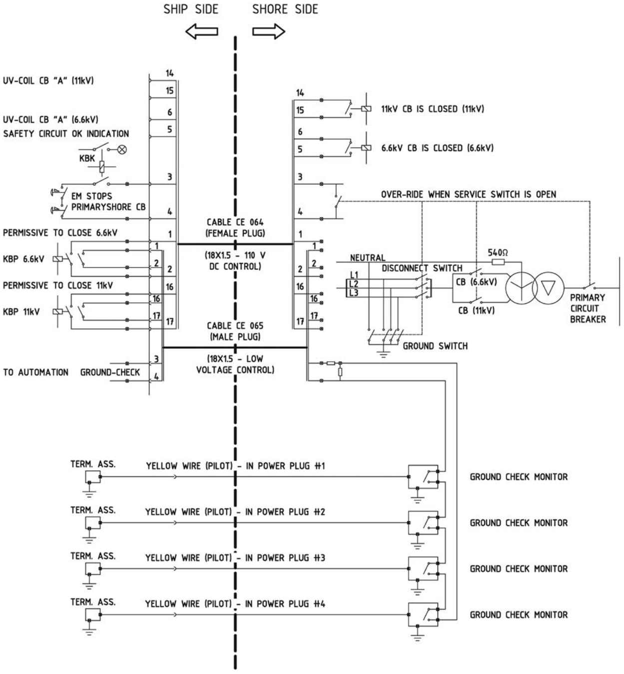


Fig. 8. ***Signals managed by the shore connection control cabinet [6].***

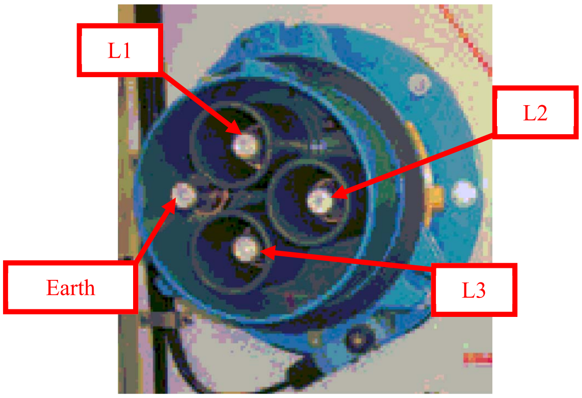


Fig. 9. ***Power and earth contacts on a power socket installed on the HVSC cubicle.***

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 the shore substation as follows:

- only one DG is to be connected to the ship's 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 stop is activated.

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

Once the shore substation transformer's secondary circuit breaker is closed and shore grid voltage frequency and phase sequences are checked, the ship officer on duty can instigate the closing sequence (phase two) by a special command on the ECR workstation. After the PMS receives the starting sequence command, the ship's shore circuit breaker "A" is closed immediately, and the diesel generator synchronizing sequence starts. First, the generator voltage is adapted to the shore side voltage acting on an alternator's automatic voltage regulator and then the frequency phase angle is also adapted acting on a diesel alternator's 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 the ship to the shore. When the power generated by the diesel generator reaches a predetermined threshold, the relevant circuit breaker is opened and the vessel receives power from the shore.

The sequence from the shore to the ship follows the same philosophy principle. In summary, first, one diesel generator is started and synchronized and connected to the ship's network supplied from the shore, then the PMS manages the load transfer from the shore to the 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.

IV. POINT OF VIEW OF THE NAVY ON MILITARY SHIPS' SHORE CONNECTION

A. General Aspects

Cold ironing is not a new standard for the Navy. Since the early 1950s, Italian vessels have had the capability to feed a distressed military ship through dedicated electrical panels and cables, at sea or in port. The need, at that time, was to establish an electrical connection between ships, rather than between the ship grid and the grid on the ground. Soon, however, there was the opportunity to use the equipment onboard for a proper shore connection. Already at the beginning of the 1970s, all the vessels had a shore connection panel and, until the end of the last century, military ships were fed at 440 V @ 60 Hz. In these cases, the required power was usually in a range from 100 kVA to 1 MVA. Section IV-B describes main features of a military shore connection. Section IV-C discusses the Italian Navy experience. Section IV-D presents the approach in the case of a new vessel design. Section IV-E presents the ship-to-shore power case.

B. Specific Features of the Military Shore Connection

At first sight, the standard of an electrical connection of military ships seems to be similar to the one of commercial vessels and cruise ships. However, there are remarkable differences between them, which are given by "operative requirements." Indeed, a vessel usually spends high percentage of its operational life in a condition called "ready to start a mission." This situation implies many features "at berth" in naval stations, as follows:

1) high standard of power quality in supplying various relevant loads (e.g., combat system's loads);
2) proliferation of voltage levels;
3) choice of frequency (50 or 60 Hz);
4) shore connection sizing relating to maximum power dimension of an electrical plant;
5) practical issues.

1) Power Quality: Loads dedicated to the combat system and, on certain ships, to hospital facilities require a very high level of power quality. This requirement is more stringent taking into account that the ship's electrical grid is fed for long periods of time (even lasting 2–3 mo) by the shore's electrical network. In particular cases, the shore grid cannot ensure power supply with high standard of power quality. In this regard, it is appropriate to focus on the requirements discussed in the Standard NATO Agreement [8]. The document specifies, among others, the standard of power quality and, in particular, it is applied to the powered equipment 440 V/115 V @ 60 Hz. The basic misunderstanding is that, for several decades, in absence of applicable standards, the STANAG 1008 has been recognized as the standard for the NATO vessel shore connection; in addition, it does not cover medium-voltage (MV) users. Certainly, a new edition of NATO Standard should address the power quality during shore connection in MV and LV, as well.

2) Level of Voltage: The voltage level (MV or LV), used for the generation/distribution board, also affects the type of cold ironing used. The large majority of warships adopt low voltage, inter alia, on different levels, as a tradeoff between the power generation and the level of fault protection. Moreover, because power required by the Italian vessels in service is less than 1–1.5 MVA (only *Cavour* needs about 3 MVA), it is not convenient to use an HVSC. Because of this, recently, the Italian Navy has selected the following alternatives:

- raising the level of voltage in the MV to decrease the cable size (e.g., the aircraft carrier *Cavour*);
- maintaining the LV level, but providing the vessel with an increased number of cables (e.g., the destroyer class *Doria*);
- adopting two shore connections, one in MV and another one in LV [a solution for the FRigates European Multipurpose Multimission (FREMM) class)].

As explained in Section IV-C, the result is the proliferation of onboard voltage levels, which is reflected in the facilities at naval stations.

3) Frequency: The choice of frequency is another important topic for shore connection. NATO warships generally have 60-Hz frequency in order to maintain high-level interoperability. Since 2002, the Italian Navy has chosen to adopt a 50-Hz distribution onboard in order to increase the use of commercial off-the-shelf (COTS) equipment, thus reducing power supply costs. As shown in mission reports, so far the Italian warships adopting 50 Hz did not show reduced interoperability during NATO missions or international exercises. So, this is the reason why the 50-Hz standard has been extended to shore connection in all Italian naval stations. Moreover, it is possible to achieve "direct matching" with the land electrical network (at 50 Hz in Europe). A 10% reduction of annual operating costs for the supply of power to ships has been estimated.

4) Shore Connection Sizing: A further requirement for shore connection of military ships is given by the different

Fig. 10. ***Navy crane.***

Fig. 11. ***Crane plugs and sockets.***

modes of operation. Comparing a commercial ship and a vessel, we notice that a warship has extra exercise modes. Indeed, in addition to the exercise modes of a commercial ship, a warship typically presents the operational harbor, combat, maximum speed, and loiter mode. Furthermore, the power required for military ships in harbor is a very low fraction of the installed power. In some cases, the power demand in harbor does not exceed 15%–20% of the maximum power required during navigation at top speed. This implies the installation of equipment or systems solely for shore connection, which is a burden on the available footprint on ships. As discussed in the part dedicated to the new ships' design, the Italian Navy has faced this issue using systems which are already installed onboard to implement the shore connection.

5) Practical Issues: Another matter of the military shore connection is the almost total absence of a standard for the cable handling systems. From a practical point of view, this represents a serious defect to users. First, it is important to clarify that, in the past, cable handling was a completely manual operation, because the cables did not exceed 35 mm in diameter (low power required). Recently, the continuous reduction of personnel aboard and the increase of the section of cables has led the Italian Navy to use different types of systems for handling of cables (electric drums and cranes). Definitely cranes seem to be the easier solution (Fig. 10). But, for managing and maintenance issues, the crane solution requires particularly skilled personnel.

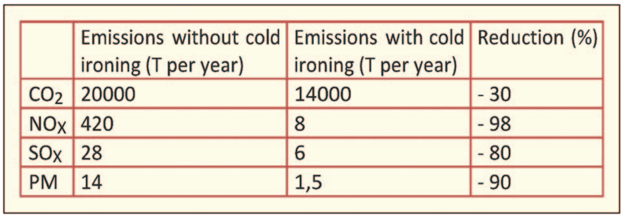
Another issue regards the sockets and the plugs. Only recently, suppliers have acted in this respect. In the past, indeed, the ends of cables (single pole or three poles) were working with extruded insulation to connect cable terminals in the switchgear (Fig. 11). So, cable terminations needed a careful connection, delaying the shore connection operations. In addition to the HVSC operation, which is covered by the IEC/ISO/IEEE Standard 80005-1 [6], the low-voltage shore connection (LVSC) operation is different. First, most suppliers are not interested in the LV socket type "fast on." Second, there is no standard approved yet on LVSC (however, this topic is currently being developed under a new draft standard IEEE/IEC/ISO 80005-3). Third, NATO Navies normally assume STANAG 1008 (which refers to power quality) as an LVSC standard.

The Italian Navy voluntarily complies with the International Maritime Organization (IMO) Convention "MARPOL" (Annex VI) and constantly monitors the feedback from naval stations (Table 1). However, it is important to note that cold ironing for naval vessels refers not only to environmental issues. Another important issue is to reduce running hours of onboard generators. Nevertheless, it is fair to admit that, in the past, shore connection was not a key driver of naval design: once the ship was built, the navies tried to find a proper solution, i.e., a tradeoff among various power/voltage levels of generation and the NATO "classic" standard 440 V/60 Hz. Today, this approach is not deemed affordable, due to the cost to facilities—on the ground and aboard—and the increasing power/voltage levels adopted on warships.

C. Italian Navy's Experience With Shore Connection

The direct consequence of the previously presented approach was the continuous modification of the ground facilities for the shore connection of vessels. For example,

TABLE 1 Taranto Naval Station Case



	Emissions without cold ironing (T per year)	Emissions with cold ironing (T per year)	Reduction (%)
CO_2	20000	14000	- 30
NO_X	420	8	- 98
SO_X	28	6	- 80
PM	14	1,5	- 90

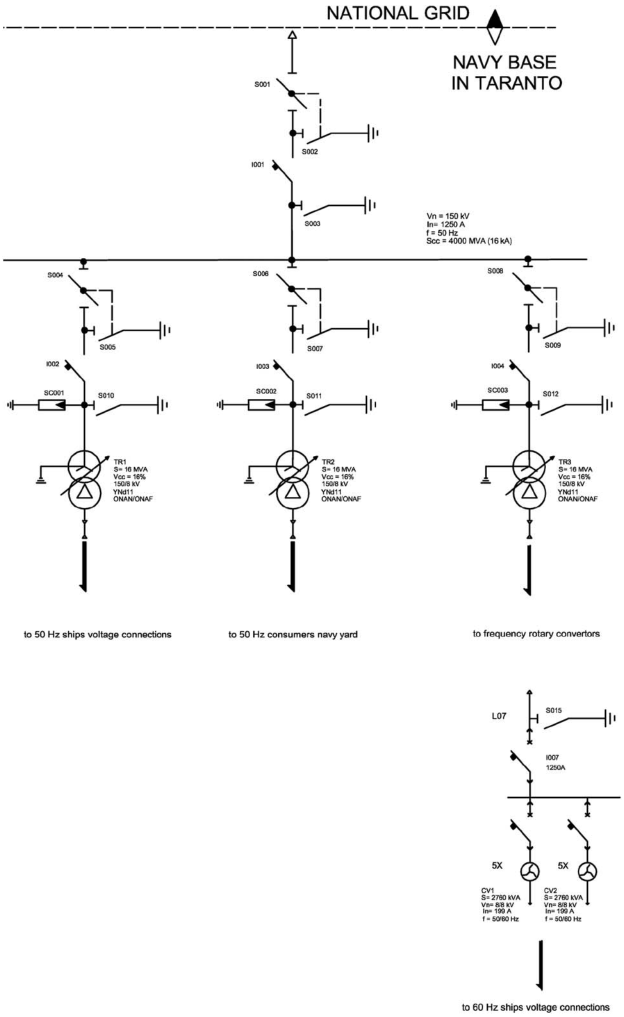


Fig. 12. ***Taranto naval station (functional diagram).***

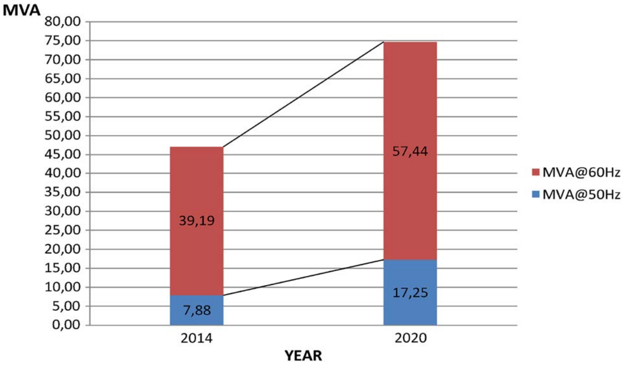


Fig. 13. ***Power required at berth.***

considering the Taranto (Italy) naval station (functional diagram in Fig. 12), we observe the following:

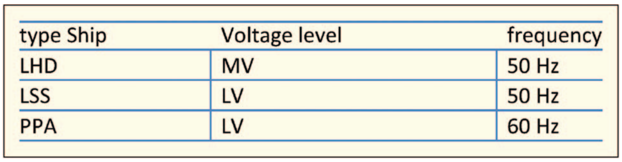
- shore connection voltage levels are very diverse, for example, 380 V @ 50 Hz, 440 V @ 60 Hz, up to 6000 V @ 50 Hz and 6600 V @ 60 Hz;
- the conversion of frequency from 50 to 60 Hz is assigned to a station, which is arranged in two groups; each one with 5 × 2760 MVA rotating machines (rotary converter). The choice of using rotating conversion groups is essentially because of the following:
  - to ensure a high level of power quality to ships;
  - to ensure continuity of service, even in case of the overload;
  - to make a galvanic isolation between the network supply and the direct supply to the naval vessels.

Note that the available 60-Hz power may be limited by the maintenance of converters, or the available power may not be enough to feed the entire vessel requirement. Considering the prediction of power for future Italian warships (Fig. 13) [9], the situation will be even worse. Therefore, in order to avoid costly (and continuous) upgrades of the cold ironing's ground facilities, the new Italian Navy program—known as the "Italian Fleet renewal"—has focused on the shore connection requirements. In particular, the project driver is the flexibility of new ships' onboard systems to be connected to the shore connection facilities already existing in naval stations.

The introduction of electric propulsion systems has changed the configuration of conventional military vessels, thereby influencing the options for cold ironing. First, the growth of power demand in "harbor mode" up to a range of 1.5–5 MVA is a matter of fact today. Second, considering STANAG 1008 and the different frequencies at naval stations around the world (50 or 60 Hz), it is necessary to achieve proper frequency conversion for shore connection. For this reason, the Italian Navy prefers to install frequency converters onboard, instead of providing conversion equipment ashore. Finally, footprints required by these systems have been greatly reduced in recent years. Therefore, as described in detail in Section IV-D, in the new ships of the Italian Navy, frequency conversion would be realized using onboard power electronics propulsion converters.

In order to extensively explain the Italian Navy experience with shore connection, it is proper to remark on an operative scenario. The broad experience of the Italian Navy and the Italian Civil Protection Department during Disaster Relief missions (e.g., Tsunami 2006, earthquake in Haiti 2010) has led the Navy to consider a number of capabilities "from the sea," available a few hours after the event and necessary for the success of humanitarian missions. The availability and readiness would be guaranteed only by military vessels near the disaster area. Among these capabilities, the Civil Protection and the Navy have also identified the opportunity to provide electrical power to a site on the ground, close to the disaster-affected areas. This procedure is called

TABLE 2 Ship Voltage and Frequency



type Ship	Voltage level	frequency
LHD	MV	50 Hz
LSS	LV	50 Hz
PPA	LV	60 Hz

"bidirectional ship to shore power," which is the capability of a warship to feed ashore facilities, such as medical services, refugee tent camps, or first aid rooms.

It is clear that the definition of the "Italian fleet renewal" is, then, a unique opportunity to make cold ironing an "enabling technology." The following considerations are thus intended to detail the design choices of new vessels in order to satisfy all the presented requirements.

D. Program of the Italian Fleet's Renewal, Commonalities, and Design Choices

The program of the Italian Navy fleet's renewal is set on three projects, relating to the classes of vessels of the logistic support ship (LSS) type, the land helicopter deck (LHD) type, and the multipurpose offshore patrol (PPA) type. The three projects are profoundly distinct not only in respect of power, but also the pair of voltage/frequency generation and main distribution systems, as summarized in Table 2.

As mentioned, the requirements for shore connection have been processed in the earliest planning stages, and they represent one of the pillars of the electrical system architecture onboard. In particular, the best solution should be a tradeoff between different instances, such as:

- to reduce the number of installed equipment onboard;
- to minimize the impact of systems (in terms of volumes and weights) on new ships for cold ironing;
- to adapt the interface with the existing arrangements in the Italian Navy naval stations, in order to minimize CAPital Expenditure/OPerating EXpenditure (Capex/Opex) costs of any new facilities on the ground;
- to minimize Opex costs of the existing facilities;
- to provide the ability in connecting the ships to the ground at 50 and 60 Hz.

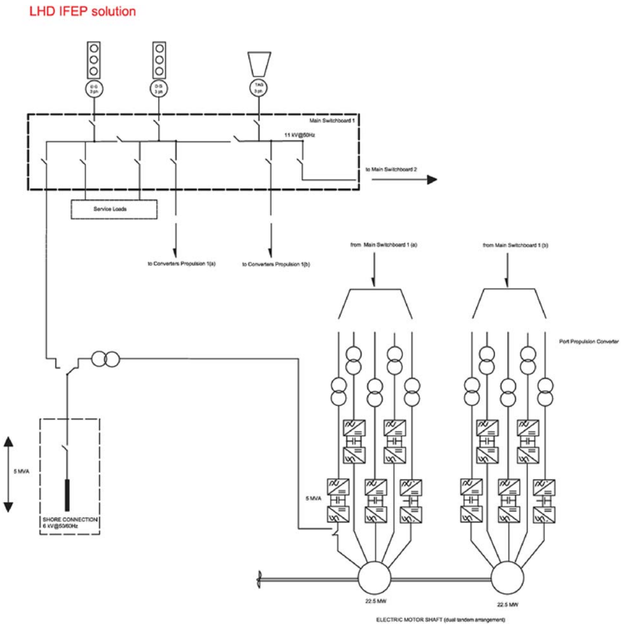


Fig. 14. ***LHD/IFEP in tandem solution.***

Two different design outputs [integrated full electric propulsion (IFEP) and hybrid] have been proposed for the LHD, where a hybrid configuration has been chosen for LSS and PPA. The related functional diagrams are shown in Figs. 14–17. In the first diagram (LHD IFEP, Fig. 14), each propulsion shaft is provided through electric motors (in tandem configuration) with a multiphase converter for each single motor. On the other hand, in the hybrid configuration (LHD, LSS, and PPA), the electric propulsion is active only at low speeds, while the high-speed one is guaranteed with conventional machines (diesel engine or gas turbine). In this case, we note a single converter control for the electric motor. In general, a practical rule has been adopted in order to reduce the number of LV and MV voltage levels: in case the ship's power generation is lower than 10 MVA, the voltage level for generation and main distribution is defined equal to 690 V. Otherwise, in presence of higher power, the voltage level is 6000 V. In both configurations (IFEP and hybrid), the frequency conversion 50/60 Hz and the voltage transformation (LV/MV) have not been assigned to a single and exclusive equipment, but to the propulsion converters.

Therefore, in the IFEP configuration (Fig. 14), the multiphase converter on each shaft line is divided into three or five sections. Then, each section is dedicated to the shore connection. For example, considering the hypothesis of a propulsion converter with five phases, each converter module is sized 5 MVA, thus determining 25 MVA for single propulsion motor, where 5 MVA is exactly the power requested during cold ironing. In the second option (hybrid, Fig. 15), the propulsion converter is designed taking into account the "loiter modes." The propulsion power demand in this case has to be equal to power required "at berth." On the other hand, LSS and PPA present different solutions: in the LSS case (Fig. 16), the converter for each shaft line supplies power from the shore to the ship grid, as well (in both cases, the requirement of power is about 2 MVA). Instead, in the case of PPA (Fig. 17), the power required "at berth" is slightly greater than the rated power of each propulsion converter (2.5 versus 1.5 MVA), therefore the propulsion converters have to operate in parallel. It is important to note that the latter solution seems to be more convenient than oversizing the two propulsion converters. Such a study, performed by the Navy design departments, the

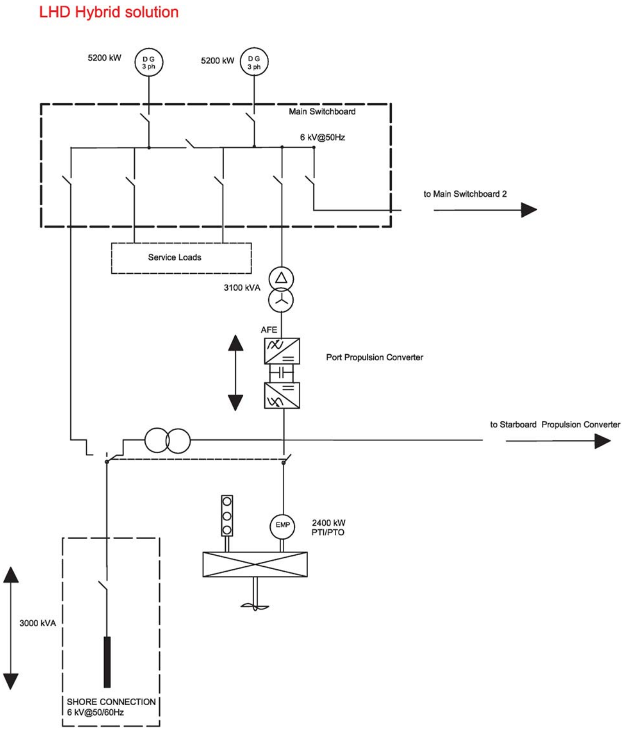


Fig. 15. ***LHD hybrid solution.***

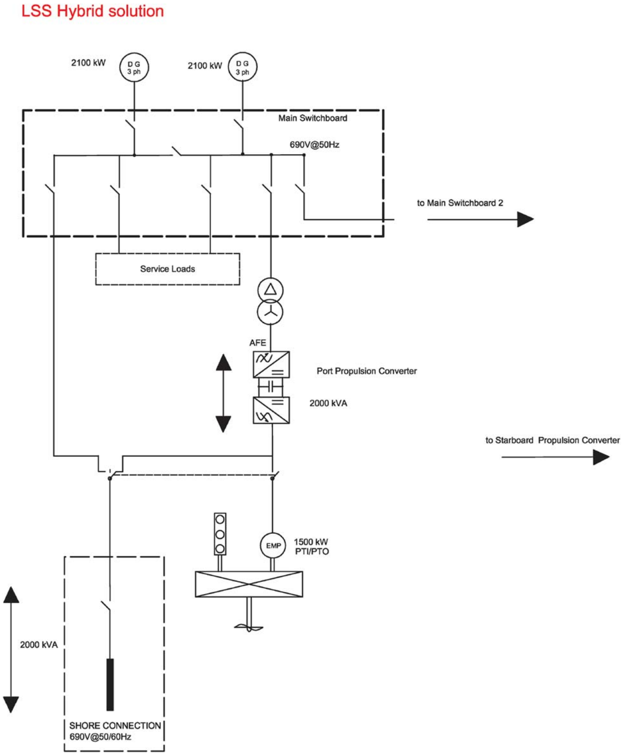


Fig. 16. ***LSS hybrid solution.***

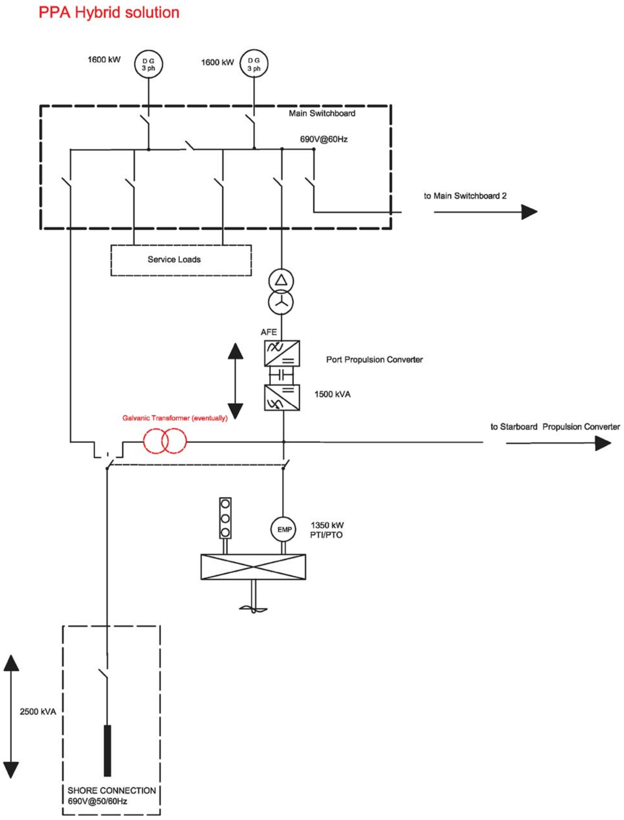


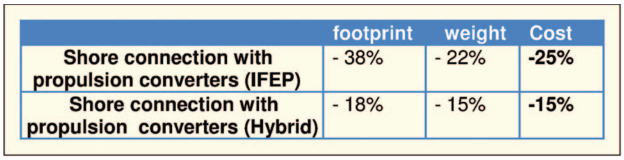
Fig. 17. ***PPA hybrid solution.***

shipyard in charge (Fincantieri SpA), and major vendors, has evaluated the gain in terms of footprint, weight, and cost (in percent) of the proposed solutions versus the system dedicated only to shore connection. The results are provided in Table 3.

E. "Ship-to-Shore Power" Solution for the Italian Navy

In the definition of the "Italian Fleet renewal" program, another ambitious goal was the "bidirectional ship-to-shore power" capability. Loads on ground are essential medical services for NATO Role 2 Plus or tent camp with "reaction housing emergency shelters" to provide first aid to people affected by disasters. Although these utilities are all in LV (400/230 V@50 Hz), the special power quality requirements of hospital facilities are noteworthy. Also, in this case, a flexible solution is recommended in order to avoid any constraint in the warship design. So, in reference to the

TABLE 3 Footprint, Weight, and Cost



	footprint	weight	Cost
Shore connection with propulsion converters (IFEP)	- 38%	- 22%	**-25%**
Shore connection with propulsion converters (Hybrid)	- 18%	- 15%	**-15%**

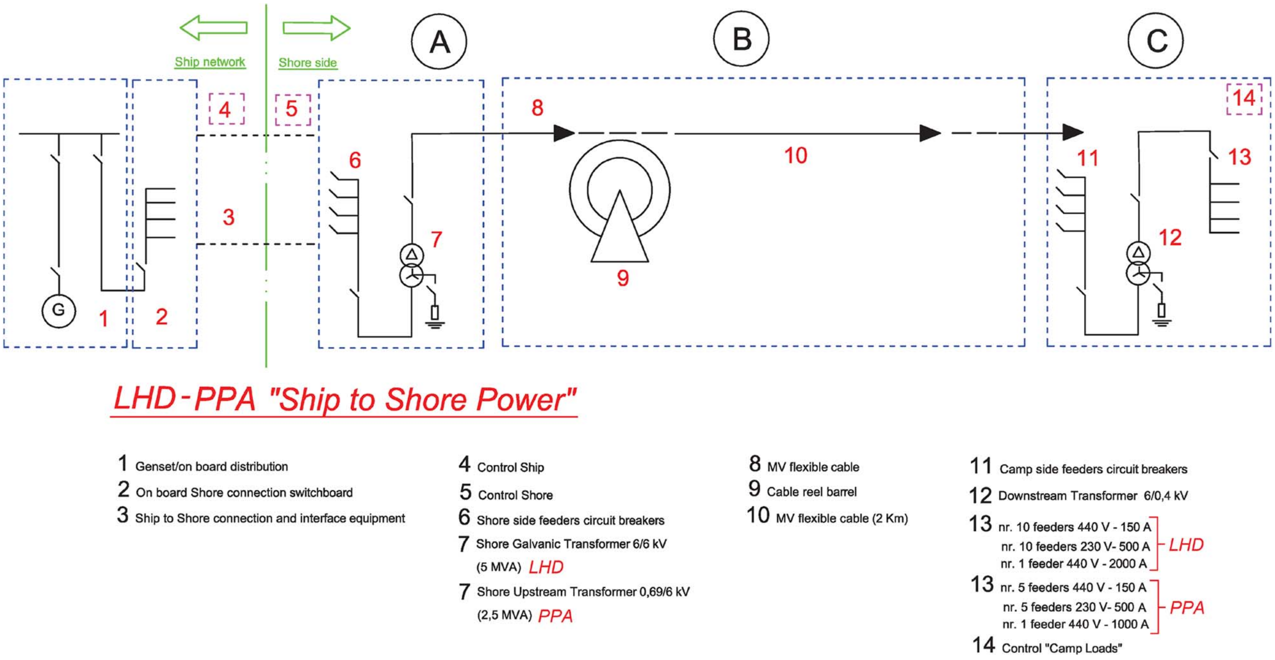


Fig. 18. ***LHD/PPA ship-to-shore power.***

solution presented in Section IV-D, a suitable interface is installed between the vessel and the site on the ground.

In practice, such a system consists in an infrastructure placed in a 40- or 20-ft container. Considering the functional diagram (Fig. 18), a set of three shelters (A, B, and C) should be used in two configurations, one for LHD and another one for PPA and LSS. In the solution for LHD (Fig. 18), there are three separate 40-ft containers. The first (A), designed for 5-MVA power, is dedicated to the transformer Dyn for earth grounding. In the second shelter (B), the drums for the reel/unreel cable (for a length equal to 2 km) are installed. Finally, the third shelter (C) hosts downstream transformer 6/0.4 kV and the switchboard feeders for end users. The only difference in the PPA/LSS scheme (Fig. 18) is the 20-ft shelter (A) to the upstream transformer 0.69/6 kV (maximum power of 2.5 MVA).

The solution set out above for the "bidirectional shore-to-ship" power is not exempt from critical issues, such as a compromise among multiple instances, often in contradiction with each other. First, the solution, in which the propulsion converter is used as a frequency converter during shore connection, requires careful analysis of the warship power quality requirements. In some cases, it may be necessary to arrange a choke system before and after the converter, or to split the front-end part as in Fig. 19. Furthermore, the solution requests a reinterpretation of the environment requirements of the machine engaged in the double function (shore to ship and *vice versa*), for example, regulations usually state a room temperature of 55 °C in the machinery room, while outside it is set equal to 45 °C.

Similarly, the space dedicated in the engine room is very poor, and it is nearly impossible to install a bidirectional converter, certainly an oversized one against the basic version (only propulsion). In particular, the solution proposed for PPA, which includes two parallel lines to power the ship, implies different "mapping" of the electrical protections as a function of the operating mode at sea. In the same manner, a further investigation will be made about the control of the two parallel converters, not installed in the same room. Another check to be performed is the need of a transformer for galvanic separation between the ship network (propulsion converter) and the ground network (see the case of PPA solution). Finally, a study, carried out by the Italian Navy and the University of Trieste, has evaluated the equipment fault protection and the electrical safety [10]. Analyzing different configurations onboard and ashore, the main result is signified by an equipotential bonding wire between the shore grounding of the substation in the shelters and the ship hull.

V. SHORE CONNECTION PROBLEMS

In the following, some problems on shore connection, mainly concerning human safety, still to be investigated, are discussed.

A. Interference of the Ship–Shore Bonding on the Cathodic Protection

Cathodic protection on small ships is often implemented by galvanic anodes attached to the hull, while impressed

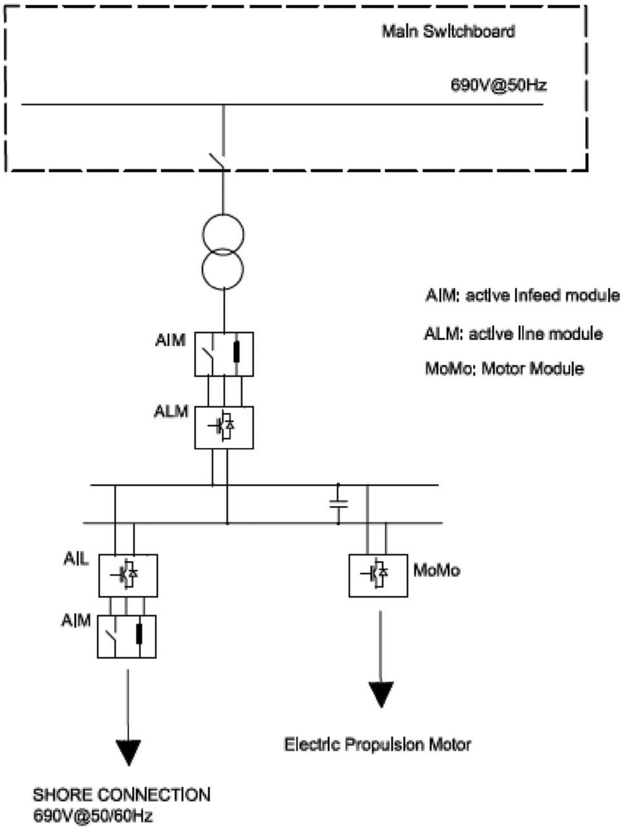


Fig. 19. ***Power quality problems solution.***

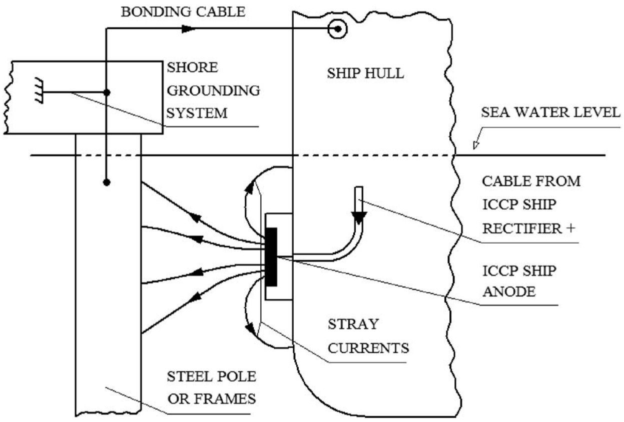


Fig. 20. ***Ship running ICCP at berth.***

current cathodic protection (ICCP) is used for larger vessels. ICCP systems have now been fitted to thousands of vessels of every type around the world. ICCP is also a common anticorrosion engineering practice for the jetties having submerged steel structures (i.e., steel foundation poles, subwater metallic carpentry, or reinforced concrete).

On both ships and jetties, the injected direct current (dc) 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 required current may be relevant. For instance, typical current density for a ship may be 25–30 mA/m^2, while for a jetty it may be around 100 mA/m^2 [11]. As a consequence of the large surfaces involved, a total of several tens, or sometime even hundreds of amperes, may be needed for corrosion protection.

When a conductive bonding between the ship and the shore, not at the same potential, is done, a large current may flow through. In this 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 the ship and the shore are plausible eventualities, but usually their effects are smaller and of fewer consequences than the ICCP ones.

For example, let us consider a ship running ICCP, moored at a jetty provided with steel pole 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 means 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 a part of the hull electrically and a fraction of the injected stray current to the jetty will close, returning to the negative pole of the ship rectifier through the bonding cable itself. We may 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 does not. This situation is reported in Fig. 21. In this case, the shore ICCP tries to protect the ship hull and the bonding allows the current to return from the hull to the negative pole of the shore rectifier.

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 the vessel and the 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,

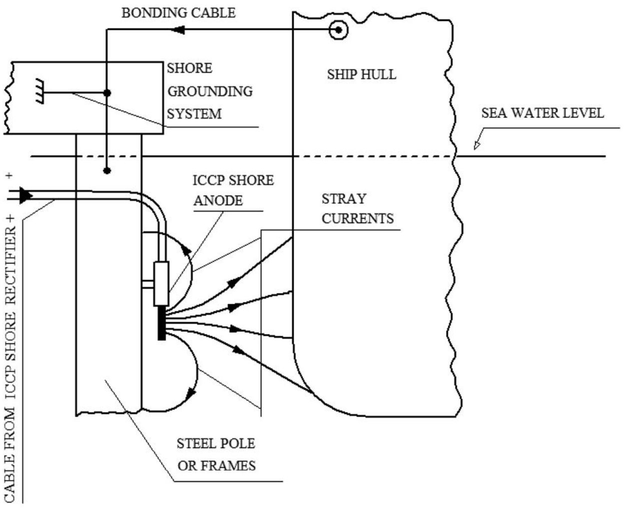


Fig. 21. ***Jetty running ICCP with a ship moored alongside.***

given by possible electrical potential differences between the ship and the jetty. The last may be of special relevance in case of hazardous flammable atmosphere presence, as is the case in oil or gas tankers as discussed next.

B. Ship–Shore Bonding in Case of Flammable Product Tankers and LNGCs

Oil and petroleum product tankers, as well as liquefied natural gas carriers (LNGCs), are a particular but widespread, class of vessels. The HVSC of this kind of ships is, as for the remaining type of vessels, also covered by the IEEE/ISO/IEC Standard 80005-1 [6]. Consequently, according to this standard, in case of HVSC, the ship-to-shore bonding is mandatory for tankers and LNGCs, 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 from 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 flammable and produce static electricity during their 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, it was common 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 this practice proves that the use of this bonding wire had no relevance in electrostatic charging. Though static electricity and charge accumulation is commonly prevented by connecting an object to earth, from the experience we know that the use of a ship–shore bonding cable does not prevent the static electricity and charge accumulation.

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 a shore hose or a loading arm is 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. Since the ship–shore bonding cable is 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 a tanker and the shore (for instance, mooring wires or a metallic ladder or gangway) could be responsible for the 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 this may be found in [12].

To be more clear, the *International Safety Guide for Oil Tankers and Terminals (ISGOTT)* Standard [13] 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* [14]. Similarly, also the applicable ISO standard for LNGCs and ship-to-shore interface and port operation [15] clearly discourages the bonding. In fact, 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 LNGCs. The IEC/ISO/IEEE Standard [6] 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 bonding (and the whole HVSC shore equipment) is located in a no hazardous area, the conflict may be bypassed. 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, depends on national and local requirements differing all around the world. Once a tanker, or an LNGC, is moored at berth, the location and characteristics of the hazardous sources of the jetty (i.e., vapor vents, valves, manifold, flanges, sampling points, etc.) and the ones of the ship have 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 situations may be a very complex problem.

C. Ship–Shore Bonding and Electrical Safety

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 an 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 a solidly grounded neutral, which means, in case of a phase-to-ground fault of the primary power supply within the port grounding, a fault current of several kiloampers will be established (in Italy, for example, values from 10 to 20 kA are common).

As is widely known, the earth fault current can split and not all of it flows through the local ground, but deeper under ground. Indeed some current (not easy to be quantified in all cases) may return directly (galvanic way) to the remote neutral through different paths, such as sky wires, cable shields, etc. According to local and national standards, considering the maximum expected ground

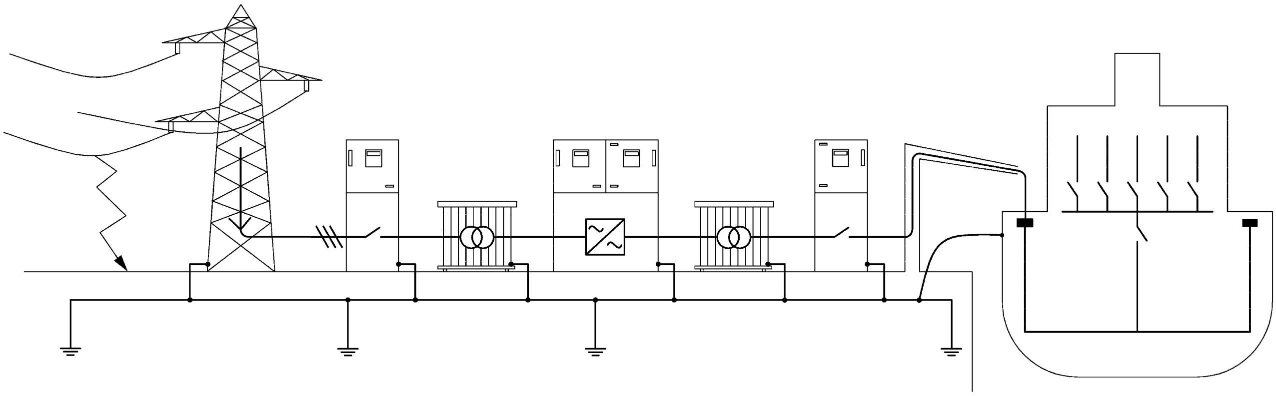


Fig. 22. ***Port with HVSC system power supply by an HV > 100-kV primary line with a single phase fault at the delivery point.***

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 similarly to what is depicted in Fig. 22.

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 from each other, at least five times the dimension of the larger net, even if the grounding system consists of unintentionally connected subsystems (considering the safety issue, not an advisable practice in most cases). The above is particularly true for cruise terminals. For tourism reasons, generally the passenger terminals are located near 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 subgrids 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) forms a unique galvanic connected rod. The direct consequence of this aspect is the generation of hull touch voltages, when a phase-to-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. In addition, 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 a gangway, or similar conducting structures).

The vessel hull is a peculiar road because of its coating. Theoretically, assuming the hull were perfectly insulated by a coating of infinite (in practice very high) resistivity, in case of a phase-to-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 other hand, a totally bare hull will generate a flat and negligible electric gradient of the potential around the ship.

In reality, we have something in between the two above extreme cases. Similarly to what happens for a majority of the anticorrosion coatings used for pipelines and similar industry applications, also a ship's coating is an insulating medium with a resistivity value that changes from the usually very good one, measurable in a lab as a sample coming in a can, to the actual existing on an aged vessel's hull in service. Once the ship's coating 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) that are microdefects within the coating itself.

The coating aging and the filling of the holidays by water during the vessel's life contribute to further progressive decrease of the bulk resistivity values. In practice, the coating of a ship still remains a semi-insulating layer during its life and a ship's hull situation is *de facto* something variable between the two extremes: a 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-to-ground fault on the primary power supply. This may happen on surface scratches, or

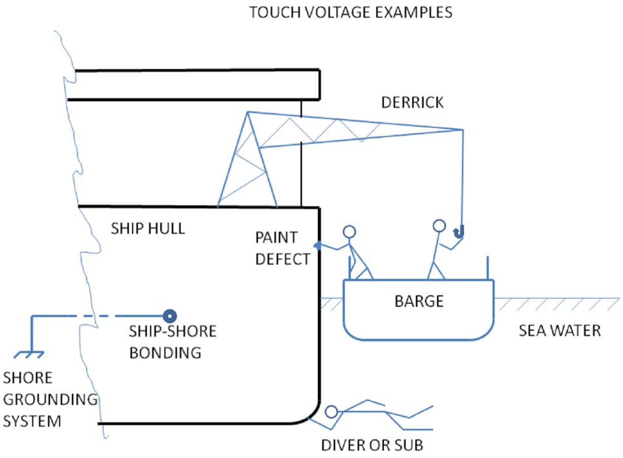


Fig. 23. ***Jetty running HVSC with a ship moored alongside.***

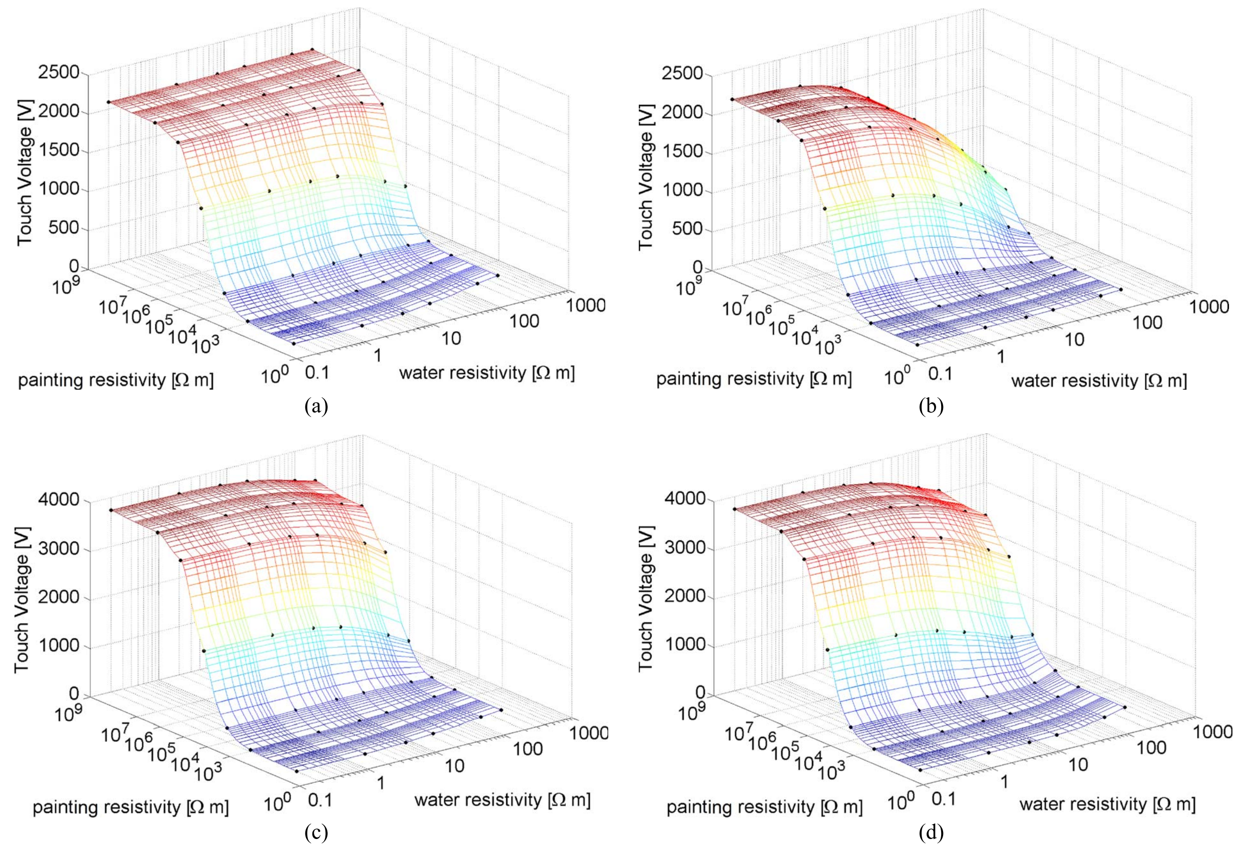
even at local breakdown points where the difference of potential exceeds the coating electric rigidity. Some potential cases are as reported in Fig. 23.

A recently published study reports on the simulation results in case of a ship with standard dimensions, bonded with a shore grounding grid, where a 10-kA current reclosing to a remote earth has been injected by a fault [16]. 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 salty 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 the finite element calculation. The computed difference of potential between the hull and a point 1 meter away from the ship is reported in Fig. 24. (In the captions, they are conventionally called "touch voltage" for simplicity instead of more correct voltage gradient, keeping in mind instances where a human being could be positioned like in Fig. 23; obviously to talk about "touch or step voltages" in water is misleading with respect to the common understanding.)

The simulation result is surprising: in case of well-coated vessels, a 10-kA single phase fault may generate a difference of potential between the hull and a point in the water (1 m away from the hull) in the range of 2–3 kV. Of course, reported results are obtained considering the schematic case of the study presented: thus, for a given port and a given ship, proposed analysis requires to be particularized to the specific case. However, the study focuses 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, we provide two categories of possible actions: 1) to establish adequate operative rules or 2) to limit the portion of the 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 cold ironing is being achieved and ships are shore bonded. Unfortunately, such easy practice in theory is not applicable in reality: indeed, forbidding service barges from approaching shore-connected ships would impair important port operations, such as bunker, garbage collections, repairs, etc.). Apparently, also an equipotential bonding between ships and servicing barges, if practicable, would improve safety in some cases, while a bonding between the ship and barges would 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 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. There 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, and then it is critical as well for the human safety evaluation. But, unfortunately, accurate computing is not easy at all in case of an HV line, as explained, for instance, in [17]. Furthermore, let us assume that the port and the supplier company's transformer stations are perfectly interconnected; it means that both installations become involved in the case of a phase-to-ground fault on the primary winding of the power supply company's transformer, where the voltage and short circuit currents are even higher. This currents reclosing to a further farer station neutral via the port and the supplier grounding, creating touch voltages on both the port and company's plants. Then, the problem is simply moved, instead of solved.
   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. We recall that



(a) (b)

(c) (d)

Fig. 24. ***Voltages, between the hull and a point at 1-m distance in water, computed in case of a phase-to-ground fault with a current of 10 kA [16]: (a) the shore ground grid located 5 m from the ship, potentials at sea side; (b) the shore ground grid located 5 m from the ship, potentials at berth side; (c) the shore ground grid located 100 m from the ship, potentials at sea side; and (d) the shore ground grid located 100 m from the ship, potentials at berth side.***

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

The magnitude of a single phase to earth fault current in an HV power system depends on the type and extension of the network and, in particular, on its zero-sequence impedance, which 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 a solid or effective grounded neutral with the growth of systems themselves, in regards to both mileage and voltage. Today, solid neutral grounding is the rule practically everywhere for systems exceeding 100 kV. A saving in system cost becomes available by the use of transformers having the insulation graded from the line terminal to the neutral, if the neutral is solidly grounded. Nevertheless, the use of a resistance grounded HV line, just for the power supply of a port, remains a practicable option to limit the single phase fault current. As a drawback, of course, the higher the resistance value is, the lower is the fault current, and the higher is the cost for reinforcing line and transformers insulation.

The solution case study discussed above was presented in [18], and it is briefly recalled here. Let us consider a situation like the one reported in Fig. 25. To limit the phase-to-ground fault current, the proposed solution is to use an HV/HV y–Δ–y (wye–delta–wye) transformer with a secondary resistance grounded neutral and with the delta coil without the connected load, at the power supply company (i.e., at the beginning of the HV power supply line).

The delta tertiary is necessary to allow the zero sequence currents flowing between the power supply and port stations. The proposed circuit arrangement is just one of the possible solutions; different circuit arrangements are also possible. In the aforementioned case study, a phase-to-ground fault current of 10 kA at the port power delivery point is assumed. The moored ship's hull is assumed to be the one considered in [16].

A voltage gradient exceeding 2000 V/m (a vessel with good condition coating and in ocean salt water) is

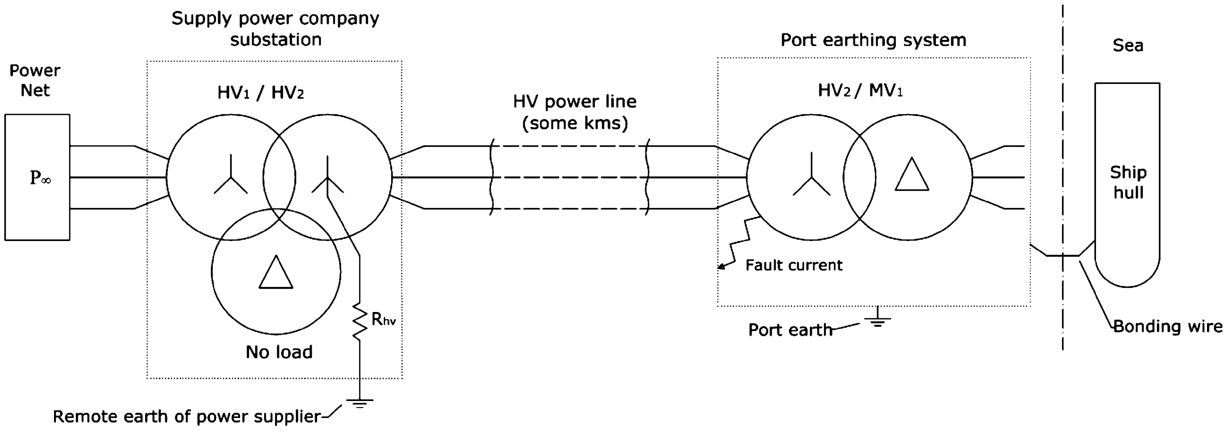


Fig. 25. ***Port power supply line with a y-Δ-y (wye-delta-wye) transformer with neutral resistance grounded at the power supply company's substation [18].***

supposed to be computed by simulations. Assuming that we would like to reduce the above gradient to a safe value, for instance, from 2000 to 30 V/m, where the current–voltage relation is practically linear, it is easy to note that the single phase-to-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} is

$$\bar{I}_{k1} = \frac{3\bar{E}}{\dot{Z}_0 + \dot{Z}_1 + \dot{Z}_2} \qquad (1)$$

where (all complexes) $\bar{E}$ is fault point phase voltage before the fault event; $\dot{Z}_0$ is an equivalent zero sequence impedance; $\dot{Z}_1$ is an equivalent positive sequence impedance; and $\dot{Z}_2$ is an equivalent zero sequence impedance.

The three traditional Fortesque's impedance circuits of the above case study power system are reported in Fig. 26.

The definitions of the symbols in the figure are as follows:

- $\dot{z}_{G1}$, $\dot{z}_{G2}$, and $\dot{z}_{G0}$ are the HHV power net sequence impedances;
- $\dot{z}_{M1}$, $\dot{z}_{M2}$, and $\dot{z}_{M0}$ are the primary power supply transformer's sequence impedances;
- $\dot{z}_{H1}$, $\dot{z}_{H2}$, and $\dot{z}_{H0}$ are the secondary power supply transformer's sequence impedances ($\dot{z}_{H0}$ includes the three time neutral ground resistance $3R_{hv}$);
- $\dot{z}_{L0}$ is the tertiary power supply transformer's short-circuit impedance;
- $\dot{z}_{PT0}$ is the port transformer's short-circuit impedance;
- $\dot{z}_{LN1}$, $\dot{z}_{LN2}$, and $\dot{z}_{LN0}$ are the HV line impedances;
- u_1, u_2, and u_0 are the positive, negative, and zero sequence phase voltages, respectively.

In the case study in [13], the calculation of I_{k1} was done for a port power 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 being done first by means of Fortesque's equations. It has been proved how, grounding the neutral with a resistance of 527 *Ω* 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 simulated in the time domain; the simulation performed has confirmed the previous result.

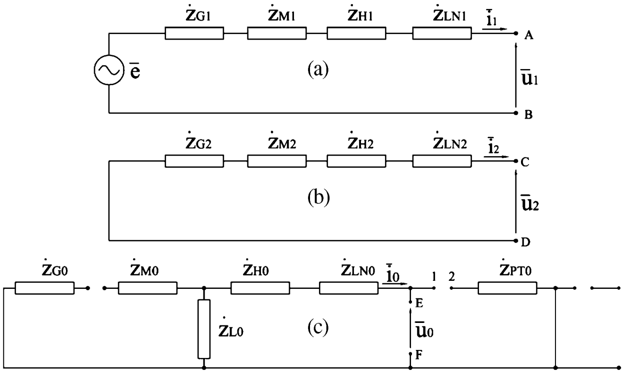


Fig. 26. ***(a) Positive-sequence circuit. (b) Negative-sequence circuit. (c) Zero-sequence circuit.***

VI. CONCLUSION

The shore-to-ship power supply state of the art has been discussed in details in this paper. Main pros are the air pollution reduction, the saving of fuel, and generators' lifetime. Main cons are the difficulties to reach a worldwide unification of voltage, frequency of both ships and shore, and electrical power systems. In this respect, the recent joint IEC–ISO–IEEE Standard (80005-1) represents a very important step in the right direction.

The points of view and field experiences on the topic of an important ship manufacturer and of the NATO's Navy have been reported. Some critical points concerning safety, to be more deeply considered and investigated, have also been discussed. It is the authors' opinion that the already initiated worldwide expansion of new shore-to-ship power facility will show a growing trend in the future on both sides, vessels and ports. ■

REFERENCES

[1] D. Bailey *et al.*, "Harbour pollution: Strategies to clean up U.S. Ports," Natural Resources Defense Council (NRDC), Los Angeles, CA, USA, 2004.

[2] International Maritime Organization (IMO), Marine Environment Protection Committee, "Prevention of air pollution from ships," Oxfordshire, U.K., 2009.

[3] Y. Khersonsky, M. Islam, and K. L. Peterson, "Challenges of connecting shipboard marine systems to medium voltage shoreside electrical power," *IEEE Trans. Ind. Appl.*, vol. 43, no. 3, pp. 838–844, May/Jun. 2007.

[4] K. L. Peterson, P. Chavdarian, M. Islam, and C. Cayanan, "Tackling ship pollution from the shore," *IEEE Ind. Appl. Mag.*, vol. 15, no. 1, pp. 56–60, Jan./Feb. 2009.

[5] European Commission, "Commission recommendation on the promotion of shore side electricity for use by ships at berth in Community ports," *Official J. Eur. Union L125*, pp. 38–42, May 2006.

[6] *Utility Connection in Port—Part 1: High Voltage Shore Connection (HVSC) Systems—General Requirements*, IEC/ISO/IEEE Standard 80005-1, 2012, ed. 1.0.

[7] A. Vicenzutti, D. Bosich, G. Giadrossi, and G. Sulligoi, "The role of voltage controls in modern all-electric ships: Toward the all-electric ship," *IEEE Electrificat. Mag.*, vol. 3, no. 2, pp. 49–65, Jun. 2015.

[8] *Characteristics of Shipboard Electrical Power Systems in Warships of the North Atlantic Treaty Navies*, STANAG 1008 Ed. 9.

[9] Italian Navy General Staff, Internal Rep. nr. 62230, Rome, Italy, Apr. 2009.

[10] A. Vicenzutti, F. Tosato, G. Sulligoi, G. Lipardi, and L. Piva, "High voltage ship-to-shore connection for electric power supply support in landing operations: An analysis," in *Proc. IEEE Electr. Ship Technol. Symp.*, Old Town Alexandria, VA, USA, Jun. 22–24, 2015, pp. 364–369.

[11] L. Lazzari and P. Pedeferri, *Protezione Catodica*. Milan, Italy: McGraw-Hill, 2000, ch. 10.

[12] SIGTTO, "A justification into the use of insulation flanges (and electrically discontinuous hoses) at the ship/shore and ship/ship interface," London, U.K. [Online]. Available: http://www.sigtto.org/media/1954/wsil-687c-sigtto-insulation-flanges.pdf

[13] International Chamber of Shipping, Oil Companies International Marine Forum, International Association of Ports and Harbor, "International Safety Guide for Oil Tankers and Terminals (ISGOTT)," 5th ed. Livingston, U.K.: Witherby Seamanship Int., 2006.

[14] Central Commission for the Navigation of The Rhine, Oil Companies International Marine Forum—ISGIN International, "Safety guide for inland navigation tank-barges and terminals," Strasbourg, France, 1st ed., 2010.

[15] *Installation and Equipment for Liquefied Natural Gas Ship-to-Shore Interface and Port Operation*, ISO 28470 Petroleum and Natural Gas Industries, 2010, 1st ed.

[16] G. Sulligoi, D. Bosich, A. da Rin, and F. Tosato, "An examination of mutual influence between high-voltage shore-connected ships and port earthing systems during phase-to-ground faults," *IEEE Trans. Ind. Appl.*, vol. 48, no. 5, pp. 1731–1738, Sep./Oct. 2012.

[17] V. Cataliotti and A. Campoccia, *Impianti di Terra*. Turin, Italy: TNE, 2003.

[18] G. Sulligoi, D. Bosich, R. Baldi, and F. Tosato, "Limiting hull touch voltages in large power shore connection systems during phase-to-ground faults: A solution proposal," in *Proc. IEEE Electr. Ship Technol. Symp.*, Arlington, VA, USA, Apr. 22–24, 2013, pp. 337–341.

ABOUT THE AUTHORS

Giorgio Sulligoi (Senior Member, IEEE) received the M.S. degree (with honors) in electrical engineering from the University of Trieste, Trieste, Italy, in 2001 and the Ph.D. degree in electrical engineering from the University of Padua, Padova, Italy, in 2005.

He spent an internship at Fincantieri Electric Systems Office, Trieste, Italy, and a semester as a Visiting Scholar at the University College of Cork, Ireland. In 2005, he joined MAI Control Systems, Milan, Italy, an Italian firm operating in the field of power stations and alternator voltage control systems. He joined the University of Trieste in 2007 as an Assistant Professor of Electric Power Generation and Control, tenured since 2010 and was appointed an Assistant Professor of Shipboard Electrical Power Systems in 2012. He is the founder and Director of the grid connected & marine Electric Power Generation and Control laboratory (EPGC Laboratory) at the Department of Engineering and Architecture. In 2013, he received the national qualification for the level of the Associate Professor in Electrical Energy Engineering. He authored more than 70 scientific papers in the fields of shipboard power systems, all-electric ships, generator modeling, and voltage control.

Dr. Sulligoi is a member of the IEEE Industry Applications Society (IAS), the IEEE Power Electronics Society (PELS), and the IEEE Power and Engineering Society (PES), where he serves in different technical and standard committees.

Daniele Bosich (Member, IEEE) was born in Trieste, Italy, in 1984. He received the M.S. degree (with honors) in electrical engineering from the University of Trieste, Trieste, Italy, in 2010 and the Ph.D. degree in energy engineering from the University of Padua, Padova, Italy, in 2014.

He is the author of about 20 scientific papers in the fields of marine shipboard power systems and voltage control.

Dr. Bosich is a member of the IEEE Power and Engineering Society (PES) and the IEEE Industry Applications Society (IAS).

Roberto Pelaschiar was born in Trieste, Italy, in 1963. He received a degree in electrical engineering from the University of Trieste, Trieste, Italy, in 1989.

He joined Fincantieri Italian Shipyards, Trieste, in 1995 and worked in the design of ships' electrical system. He is a member of CEI TC18, serving as a secretary; IEC expert for TC18, the Italian Technical Committee Lloyd Register. He collaborates with Trieste University as an expert on a ship electrical plant. Currently, he works for Fincantieri Company as Head of Electrical Power, Automation and Safety System office. He also is devoted to educational activities for the electrical plant in Fincantieri and to research activities in the ship electrical plant.

Gennaro Lipardi was born in Naples, Italy. He completed his secondary studies at the Military School ''Nunziatella'' (the oldest one in Europe) and attended the Italian Naval Academy (1993–1997). He received the M.S. degree in naval engineering and naval architecture from the University of Naples, Naples, Italy, in 1999 and the M.S. degree in electrical engineering from the University of Rome, Rome, Italy, in 2010.

At sea, he served as technical officer aboard *ITS Garibaldi* (CVS 551) and *ITS Mimbelli* (D 561). His first Chief Engineer assignment was *ITS Bettica* (P 492) and then his Major Chief Engineer assignment was *ITS Cavour* (CVH 550), where he was involved in supervising of shipbuilding and commissioning of the Aircraft Carrier. He is currently assigned an Electrical Plants & Naval Automation Office of Naval Directorate, where he is responsible for electric procurement of surface combatants, amphibious ships, and logistics support ships. He is a permanent member of the Italian Electrotechnical Commission. He is also responsible for related military (for the Navy) relationship with South America and, in particular, with Argentina and Venezuela. His shore responsibilities include Research & Development Department of General Staff of the Italian Navy (Electrical Plants) and Research & Development Department of General Staff of Italian Ministry of Defence. His interests cover all applications of electrical technology aboard military ships.

Fabio Tosato received the Dr.Ing. degree (*cum laude*) in electrical engineering from the University of Trieste, Trieste, Italy, in 1967.

In 1967, he joined a multinational oil company, where worked until 1985, and advanced to the level of Operative Director. In 1985, he left the industry and joined the University of Trieste as an Associate Professor, later becoming a Full Professor. He is the author of more than 100 scientific papers covering several power system topics such as power delivery, power quality, cathodic protection, and short circuit. He is currently retired from teaching but is still cooperating with his former university group on some research programs.

Dr. Tosato is a Registered Professional Engineer in Italy.