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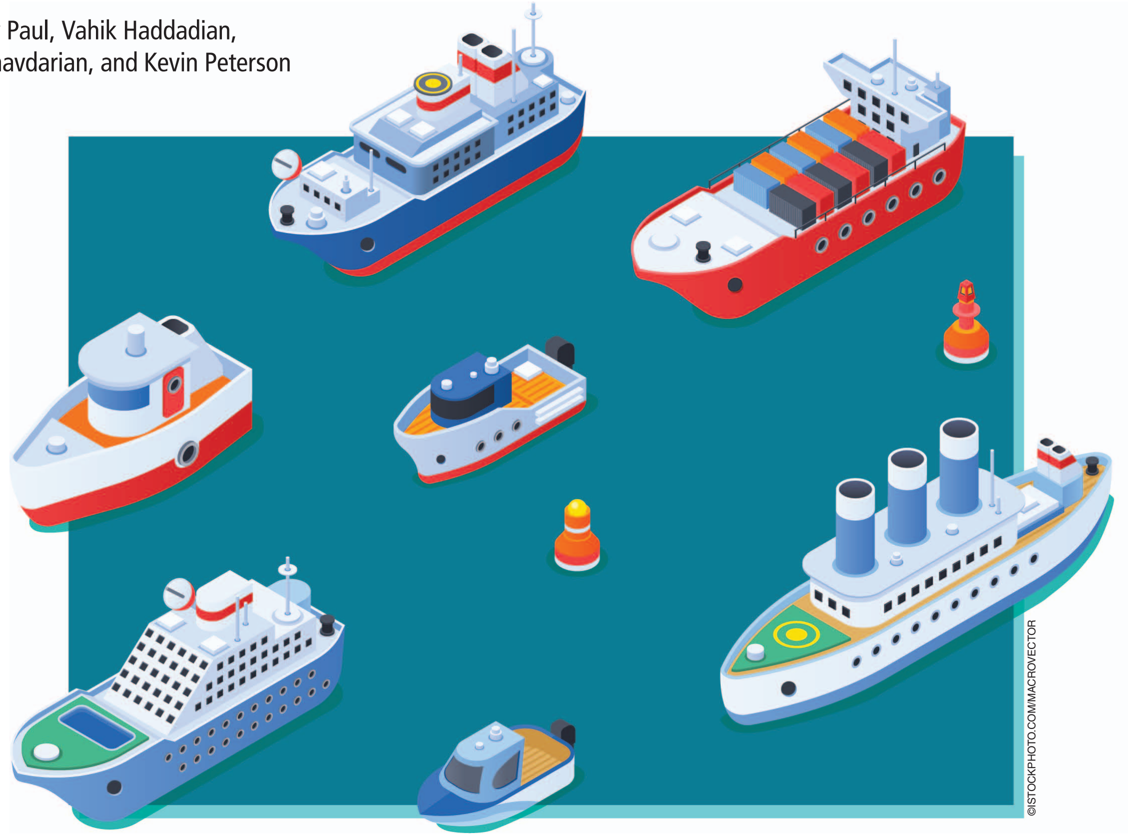

Low-Voltage Shore Connection Power Systems

OPTIONAL DESIGNS AND A SAFETY LOOP CIRCUIT

THIS ARTICLE REVIEWS LOW-VOLTAGE SHORE CONNECtion (LVSC) power systems for ships with up to 1,500 kVA and voltage of 400–690 V. The design concept for these systems is contained in the current LVSC draft standard, International Electrotechnical Commission (IEC)/IEEE 80005-3. Here, we attempt to clarify that an LVSC design concept using multiple parallel feeder circuit breakers does not violate National Electric Code (NEC) National Fire Protection Association (NFPA) 70 Section 240.8. We also attempt to clarify the optional design for an ungrounded shore power system, as required by certain ships and included in the draft standard [1]. In addition, we review the safety loop circuit that enhances operator safety both onshore and onboard a ship.

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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 [11], [12], [14]. 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 [1]. 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

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are necessary to meet shore power requirements. Up to five parallel feeders are needed for ships rated 1,500 kVA at 400 V [1].

Individual plug/receptacle (plug/socket) assemblies and their associated feeder cables require overload and short circuit protection per NEC NFPA 70 [2], and thus an overload and short circuit protection scheme should be applied. One such scheme 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 Figure 1 (reproduced from [1, Fig. 1]).

In this article, we first describe the block diagram for an LVSC power system. Then, we present a power system protection-relaying diagram that shows the logic of an interlock between the feeder breakers and the main circuit breaker. Based on the technical and safety discussion included, our article recommends 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 backfeed power from the parallel feeders to the faulted location will be stopped with little or no damage. This article includes 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. This interpretation, which has been 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 [1].

This article reviews 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 [4], the neutral resistor will be sized as 5-A 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 Figure 1 (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.

We recommend against using an ungrounded power system, as the equipment is subject to the threat of unpredictable transient surges, which can lead to damage and compromise safety [3]–[5], [8]. It is logical that the port can work with those ship authorities that require ungrounded shore power supply to equip onboard isolation transformers (item 11 in Figure 1) and not use a neutral disconnect switch and the associated dedicated interlock scheme needed to operate as an ungrounded power system. Later, we provide reviews of the safety loop control schematic, similar to one used in [12] to enhance the safety of the operators during cold-ironing operation.

LV Power Supply System

Figure 1 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

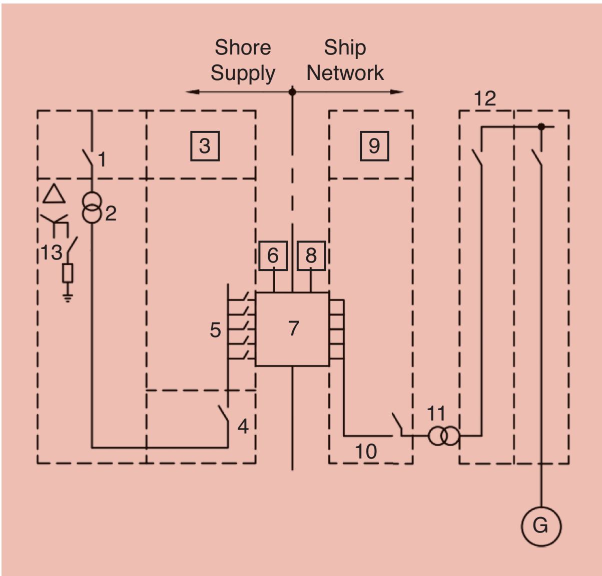

FIGURE 1. An LVSC block diagram: the 1) primary breaker, 2) substation transformer, 3) LV switchgear, 4) main breaker, 5) feeder breakers, 6) feeder cables to power receptacles, 7) plug and receptacle assemblies, 8) plug with a flexible cable, 9) ship onboard shore power panel, 10) ship-side circuit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

system is available [15]; thus, for simplicity it is not shown in this article. A neutral disconnect switch providing an ungrounded power system, as required by some ships indicated in the standard [1], 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 Figure 1) 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 described in the "Overview of LVSC Power Systems" section 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, we propose an alternative: create an HRG grounded power system using a 2-A 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.

Power System Protection

NEC 240.8 [2] 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 breakers, along with other control relays and interlock devices [all Underwriters Laboratory (UL)-labeled components], 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 Figure 2.

Figure 2 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 [1] are shown in this protection scheme using standard LV circuit breakers [3], [5]–[7]. 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 Figure 3) 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 Figure 2 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 [1] 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 backfeed from the parallel feeders by tripping the main breaker as soon as the faulted feeder breaker trips.

Table 1 shows the number of parallel feeders required to connect ships with different kilovoltampere power demands at different supply voltages. Figure 2 shows a fault on feeder F_1 to illustrate how all parallel feeders can contribute to backfeed 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 [1]. As described in [1], 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. The construction of switching equipment onshore with a main breaker and feeder breakers can be a switchboard type, listed per UL891, or a switchgear type, listed per UL1558.

Kirk Key Interlocks

Each plug/socket (plug/receptacle) assembly will have a Kirk key interlock (mechanical interlock [1]) 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 Kirk key interlock testing with the desired plug/socket assemblies and emergency trip interlocks shown in Figure 3. To provide permissive logic before implementation of the

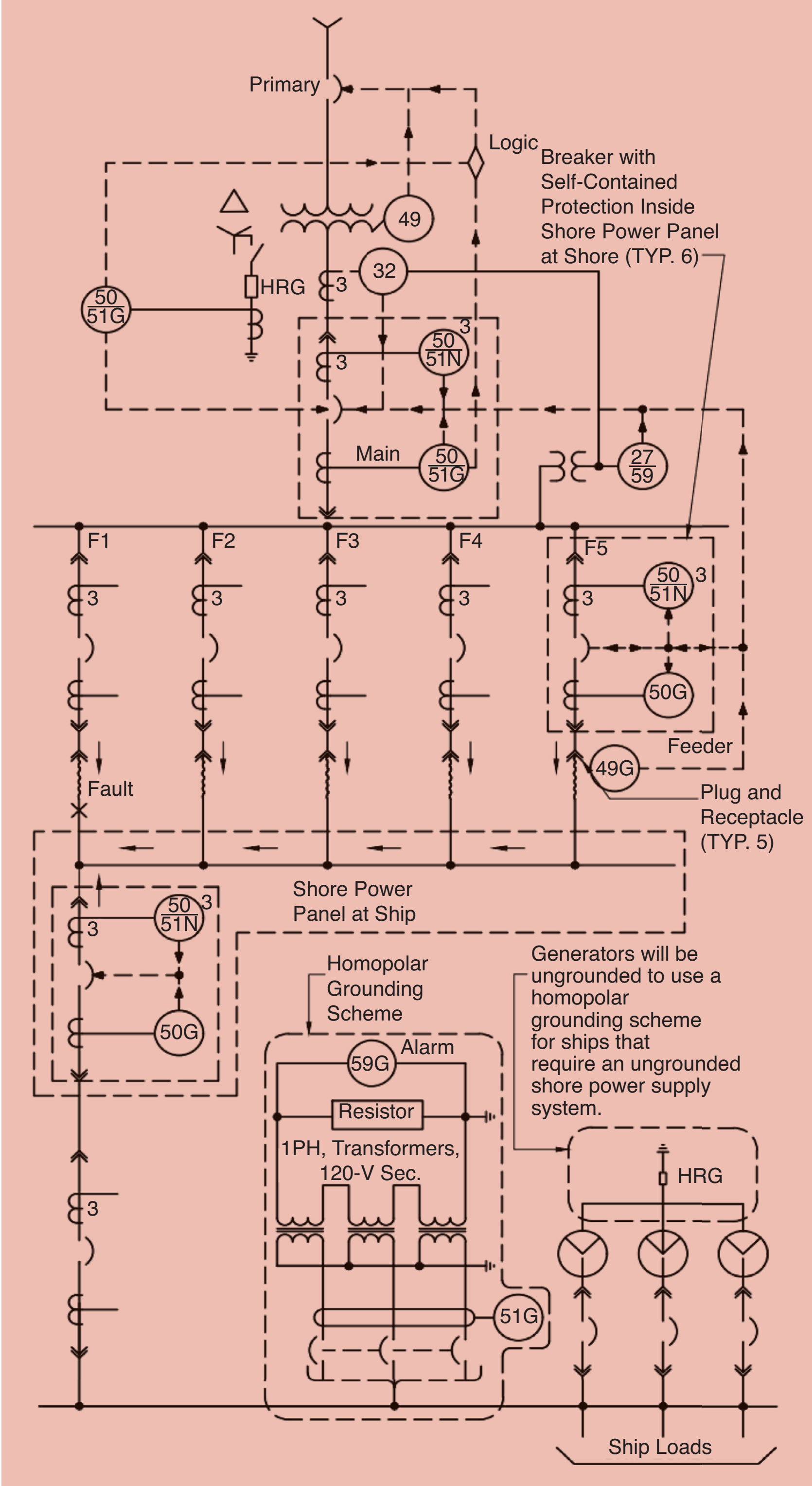

FIGURE 2. A one-line diagram of a shore-to-ship power system protection scheme. The logic to trip the primary breaker is as follows: when the main breaker does not sense ground fault and the neutral relay senses ground fault, they provide a trip signal to the transformer primary breaker, as the fault 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 [1, Figs. 3 and 4]. TYP: typical; Sec: secondary.

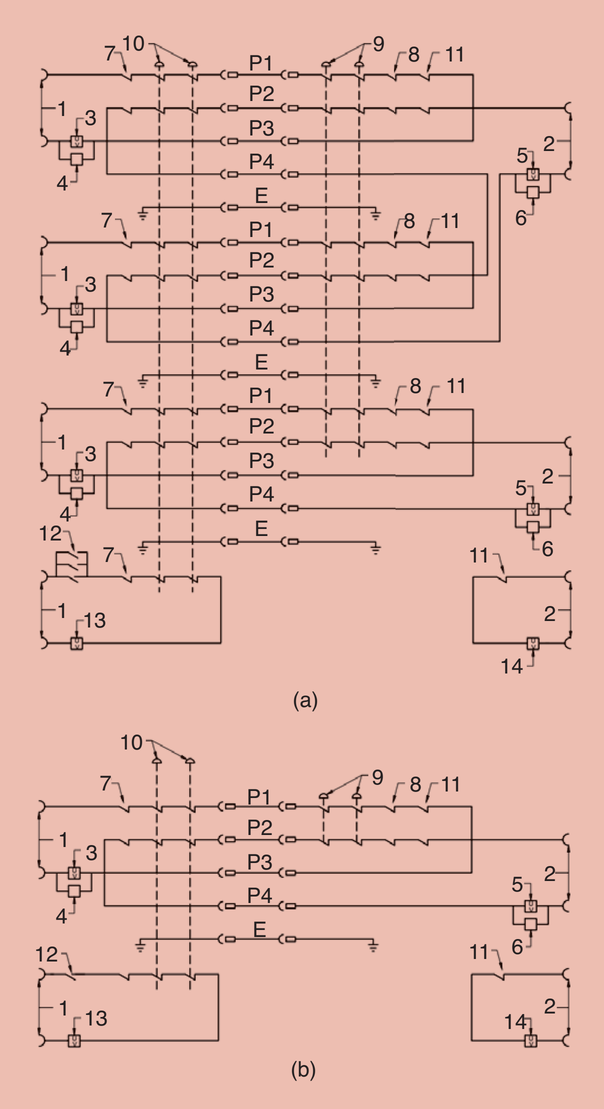

FIGURE 3. A safety loop schematic: (a) a circuit for three feeders and (b) a circuit for one feeder. 1) The control power pilot loop shore, 2) control power pilot loop ship, 3) feeder circuit breaker under the voltage coil (shore), 4) safety circuit coil on shore, 5) main circuit breaker under the voltage 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.

synchronizing scheme that will close the ship circuit breaker (item 12 in Figure 1), the ship switching equipment will require similar separate Kirk 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.

Table 1. The parallel feeders for various ship power demands

	Voltage (V)		
Power Demand kVA	**400**	**440**	**690**
Up to 250	2	1	1
251–500	3	2	2
501–750	4	3	2
751–1,000	5	4	3

Ground-Fault Protection

HRG ground-fault protection using a 5-A continuous neutral grounding resistor [1] is recommended. This method of grounding a shore power substation transformer neutral employs maximum resistor (R) in ohms by using (1) to make an HRG system [4]. However, using a 5-A 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. We consider a 5-A resistor 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 [14] to keep the criteria shown in (1) applicable for different ship voltages:

$$R = \leq \left(\frac{E_{LN}}{I_C}\right), \tag{1}$$

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 shore-side 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 Figure 2, 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 [17].

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

$$I_{GF} = \sqrt{I_{\text{Requivalent}}^2 + (I_C)^2}\,. \tag{2}$$

The value $I_{\text{Requivalent}}$ is the combined equivalent resistive component of the fault current derived using (3), where the shore power transformer neutral resistor and ship generator neutral resistor are R_{Shore} and R_{Ship}, respectively:

$$I_{\text{Requivalent}} = (E_{LN})\left(\frac{(R_{\text{Shore}})+(R_{\text{Ship}})}{R_{\text{Ship}} \times R_{\text{Ship}}}\right). \tag{3}$$

The total capacitive component of the fault current (I_C) will split between shore and ship power sources as $I_{CGF\text{Shore}}$ and $I_{CGF\text{Ship}}$, respectively, resulting in fault currents from two power sources related by (4) and (5) as follows:

$$I_{GF\text{Shore}} = \sqrt{I_{R\text{Shore}}{}^2 + (I_{CGF\text{Shore}})^2}, \tag{4}$$

and

$$I_{GF\text{Ship}} = \sqrt{I_{R\text{Ship}}{}^2 + (I_{CGF\text{Ship}})^2}, \tag{5}$$

where

$$I_{CGF\text{shore}} = -3I_{CO\text{shore}}, \tag{6}$$

$$I_{R\text{Shore}} = \left(\frac{E_{LN}}{R_{\text{Shore}}}\right), \tag{7}$$

$$I_{CGF\text{ship}} = -3I_{CO\text{ship}}, \tag{8}$$

and

$$I_{R\text{Ship}} = \left(\frac{E_{LN}}{R_{\text{Ship}}}\right). \tag{9}$$

The value I_{CGF} represents the capacitive component of the phase–ground-fault current, which is at 180° to the system charging current ($3I_{\text{CO}}$) and is thus shown with a negative sign in (6) and (8) for the shore and ship. E_{LN} is line-to-neutral voltage. The splitting of capacitance between the shore and the ship is not precise. Thus, (4) and (5) are more theoretical; it is more practical to use (2) and (3). The expected phase–ground-fault currents indicated in Table 2 are based on a 5-A shore transformer neutral grounding resistor and a 1-A 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.

Ships with ungrounded power systems connect to ungrounded shore power systems as indicated in [1]; such ships are normally equipped with bus-connected homopolar grounding schemes [17] 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 in the “LV Power Supply System” section. If certain ships require an ungrounded shore power supply, as indicated in [1, Annex D], then the best option is to have ships equipped with an isolation transformer but keep the shore power system grounded.

Safety Loop Circuit

The safety loop control schematic shown in Figure 3 is a reproduction from [1, Fig. 6]. 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 [1]. 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. Figure 3 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 [Figure 3(a)], 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.

Power Plug and Socket

The power plugs and socket outlet shown in Figure 4 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. We refer to this device as a Kirk key interlock device. 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.

Conclusions and Recommendations

The following conclusions and recommendations can be drawn from this article.

Table 2. The expected ground-fault current

Phase–Ground-Fault Description	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

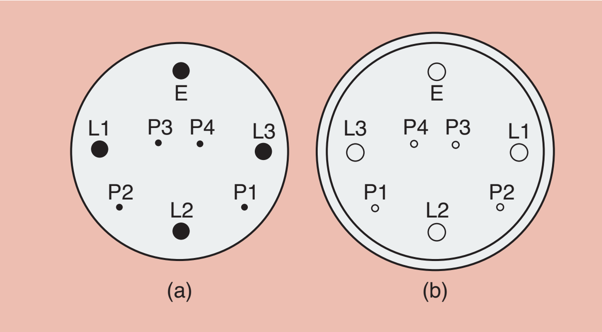

FIGURE 4. The power plug and socket pin assignment. (a) The plug/ship inlet face and (b) the socket-outlet/ship connector face. E: earth; L1: phase 1–A–R; L2: phase 2–B–S; P1: pilot 1; P2: pilot 2; P3: pilot 3; P4: pilot 4.

1) The design of LVSC equipment onshore can be a switchboard, per UL891, or switchgear, per UL1558. LVSC shore-side switching equipment with a main breaker interlocked with feeder breakers can be designed to meet the technical requirements included in [1]. 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 (AHJ) over approval of port LVSC design, per [1] as described in this article, 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 [1] 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 [17] 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) We recommend the need for an exception by including a footnote clarification to NEC 240.8 in the next (2020) edition of code [2] to allow LVSC [1] with main and parallel feeder breakers.

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