Challenges of Connecting Shipboard Marine Systems to Medium Voltage Shoreside Electrical Power

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***Abstract*—Ship service electrical power consumption at the pier side is rapidly growing and now exceeds 10-MW power range on many of the latest commercial ships. Short circuit current interruption capability of the switchgear and cables servicing the ship load at the port dictate the use of medium voltage power distribution systems at voltages from 5- to 21-kV range. Many of the high power medium voltage electrical loads must operate during unloading and loading of the docked ships. At the same time, environment protection regulations in many sea ports (California's largest ports are examples of the most restrictive requirements) do not allow ships to operate their prime movers while at berth. Many ship operators and port authorities are struggling with the absence of appropriate standards and specifications for interconnecting the ship service loads to onshore power distribution systems. The intent of this paper is first to review the theory, practice, and existing interconnection standards and then to outline what can be done to achieve a secure, reliable, safe, and cost-effective operation of the ship service loads inside international ports. This paper will review the current state of cold ironing, existing applicable standards for ship interconnections to shore power, proven techniques for shore power interconnections, as well as approaches to mitigate challenges of high power and high voltage shore power.**

***Index Terms*—American Bureau of Shipping (ABS), cold ironing, Det Norske Veritas (DNV), Environmental Protection Agency (EPA), IEEE-45, IEEE-P1662, International Electrotechnical Commission (IEC), Lloyds, Mil-C-24368, shoreside power.**

I. Introduction

INTERNATIONAL shipping has improved the quality of life tremendously by transporting refrigerated goods container ships, cruise ship industry, bulk goods carriers, tankers loading and unloading oil, etc. In present day technology, the speed of performing these tasks provides economic advantage for the ports. The shoreside operation of these ships (vessels by American Bureau of Shipping (ABS) and Lloyd Register definitions) demands more electrical power than the traditional shipboard shore power. Natural Resources Defense Council in its August 2004 report "Strategies to Clean up the U.S. Ports" [1] indicated that marine ships contribute substantial quantities of air pollution by running onboard diesel auxiliary engines for power while they are at dock. This "hoteling," as it is known, contributes significant but unnecessary pollution, which is aggravated by the fact that auxiliary engines run on bunker fuel—the dirtiest grade of diesel. This measure, therefore, employs a strategy of connecting docked marine ships to less polluting power sources and is a critical step to reduce emissions from marine ships.

Plugging into shoreside power, which is also known as "cold ironing," should make use of near-zero or zero emissions generation technology to provide cleaner power to docked ships. Several ports throughout the world, including Los Angeles, CA; Juneau, AK; and Gothenburg, Sweden, have already implemented shoreside power measures. Specifically, this measure calls for ports to:

1) require shoreside power as a condition of new terminal leases or renewals;
2) invest in infrastructure for electric power;
3) develop shoreside power for port-operated facilities;
4) subsidize the development of shoreside power for harbor craft;
5) provide funding to offset the costs of retrofitting ships to accommodate shoreside power.

The Swedish port of Gothenburg has led the way on commercial shoreside power installations. The system has operated since the year 2000 without problems. It utilizes a 10-kV cable and transforms the electricity onboard to 400-V dc. Shore power is supplied by local surplus wind generated power. Terminal operators make the power connections and disconnections. It takes less than 10 min to complete the process.

The ships' hoteling power demand ranges from 1 to 1.5 MW. The Gothenburg project alone has reduced 80 tons of NO_x, 60 tons of SO_x, and 2 tons of particulate matter (PM) emissions annually because of shoreside power used by ferries and several cargo ships.

The Princess Tours cruise line followed suit in 2001, installing shoreside power at its terminal in Juneau, after incurring several fines averaging $27 500 each for visible smoke from its cruise ships. Although some minor technical difficulties arose during the design and construction phases of the project, they proved surmountable. In fact, Princess reports that the project is working well and that it is pleased with the program overall.

In 2002, the City of Los Angeles signed a memorandum of understanding (MOU) with six shipping lines to participate

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TABLE I
ESTIMATED AVERAGE ONBOARD POWER REQUIREMENTS

Ship Type	Ship Name	Gross Registered Tonnage	Number of Generator Engines	Installed Generator Capacity (kW)	Average Load (kW)	Load Factor (% of capacity)	Cost Effective Yes /No
Container ships	*Victoria Bridge*	47,541	4	5,440	600	11%	No
	Hanjin Paris	65,453	4	7,600	4,800	63%	Yes
	Lihue	26,746	2	2,700	1,700	63%	No
	OOCL California 2	66,046	4	8,400	950	62%	Yes
Reefers	*Chiquita Joy*	8,665	5	5,620	3,500	62%	Yes
Cruise ships	*Ecstasy*	70,367	2	10,560	7,000	66%	Yes
Tankers	*Alaskan Frontier*	185,000	4	25,200	3,780	15%	Yes
	Chevron Washington	22,761	2	2,600	2,300	89%	No
	Groton	23,914	2	1,300	300	23%	No
Dry bulk	*Ansac Harmony*	28,527	2	1,250	625	50%	No
Auto carrier	*Pyxis*	43,425	3	2,160	1,510	70%	No
Break bulk	*Thorseggen*	15,136	3	2,100	600	29%	No

in the development of the alternative maritime power (AMP) program at the Port of Los Angeles (POLA). This MOU acknowledged the signatories' intent to research and develop an electric infrastructure that would allow ships to plug into electric power while at berth (shoreside power).

The POLA unveiled the world's first electrified container terminal in June 2004, where ships can plug in to shoreside power while at berth instead of continuously running their dirty diesel engines to generate electricity. The new China Shipping Line terminal facility is expected to eliminate at least 1 ton/day of nitrogen oxides and PM for each ship that plugs in and can accommodate two ships at one time, according to the POLA.

The Port of Long Beach (POLB), California, completed its yearlong feasibility study in early 2004 on electric power for ships at berth and found shoreside power to be cost-effective for some applications including cruise and container ships [2].

The estimated average onboard power requirements for the selected ships in the study are presented in Table I.

Only five ships with medium voltage distribution systems have been found to be cost-effective.

Other Northern European ports, such as Lubeck, Germany, are currently seeking to establish standard technical requirements for cold ironing in Baltic ports and to implement cold ironing. The port plans a 10-kV onshore connection for its ferry and passenger terminals. The city is adjacent to a town known for its health spa but SO_2 thresholds are exceeded in the winter, thereby risking the town's reputation. Surplus wind-powered energy in Lubeck would make onshore electricity cost only one-fourth the price of onboard generation.

The City of Lubeck is working on a more extensive cold ironing "Plan Baltic 21," with all Baltic port cities.

II. Current State of Cold Ironing

The summary of current applications of cold ironing around the world that was extracted from the reference "Cold Ironing Cost Effectiveness Study" [2] is given in Sections II-A–E.

A. Princess Cruise Ships in Juneau

The first cruise ship cold ironing installation anywhere in the world was in Juneau. On July 24, 2001, the Princess Cruise ship *Dawn Princess* operated completely on shore power for about 10 h. By the 2002 cruise season, all five Princess Cruise ships were converted to use shore power when they moored in Juneau. The application serves Princess passenger ships only—no cargo ships use the facility.

Shore power is supplied by Alaska Electric Light and Power (AEL&P) from its local surplus hydroelectric power. The Juneau cold ironing system provides both electric power and steam, which is produced by an electric boiler. It should be noted that even at dock the ship's boilers are run in a low-fire mode to prevent excessive smoking on start up. Significant cost (approximately \$150 000 each ship) was incurred to modify the onboard power management software to synchronize the onboard power with the onshore supplied power. Each ship was outfitted with a new door, an electrical connection cabinet, and the necessary equipment to automatically connect the ship's electrical network to the local onshore electrical network.

Each ship's technical office area on deck 4 was used as the point of entry for the power connection. A 4×2.5 m steel bulkhead was installed between adjacent steel decks to provide the A-0 fire class condition required to connect to a high voltage (6.6 kV) power source. The Sun Class ships have four Sulzer 16ZAV40S engines driving four GEC generators delivering 6.6-kV three-phase 60-Hz power. Each Sun Class ship was originally constructed with one spare 6.6-kV breaker on its switchboard. The cable connection on the ship is a traditional male/female plug and socket that was adapted from the American mining industry.

Electrical power is transmitted from a three-stage transformer onshore via four 3-in diameter flexible cables that connect to the ship. A special 135-ft-long 25-ft-high gantry system was built into the dock to support the connecting equipment, connection cables, and plugs. Transmission equipment was designed to accommodate a 20-ft change in the tide level and to withstand 100 mi/h winds. The cable connection and disconnection is performed by the Princess Cruise crew, but the shoreside substation is operated by the AEL&P personnel. The time required to pull the cables aboard, connect them to the ship controls, and begin to run the ship on onshore power varies from 20 min to 2 h. The same amount of time is needed for disconnecting shore power. Process safety is addressed through personnel training and implementing process checklists.

The onboard power management system software was modified to recognize the onshore power supply as an additional (the fifth) onboard power-generating unit. The software synchronizes the onboard power with the onshore supplied power, adjusts the onboard voltage until it matches the onshore supply, and then regulates the onboard frequency and phase until they match the onshore supply characteristics.

Princess Cruises Sun Class ships require about 7 MW of power at 6.6 kV, but the Grand Class will require 11 MW at berth. Princess Cruise Line is near completion of cold ironing its newest ship—*Diamond Princess*—at the Port of Seattle. The *Diamond Princess* was delivered to Princess Cruise Line in April 2004. It had all of the equipment required for cold ironing installed during construction. Power demand at berth is expected to be between 8 and 9 MW.

B. Pohang Iron and Steel Company (POSCO) Dry Bulk Ships in Pittsburg, CA

POSCO charters four dry bulk ships, from Pittsburg, for ocean shipments between South Korea and the San Francisco Bay Area. The ships are cold ironed at the POSCO Pittsburg docking facility. The four ships were built in South Korea between 1991 and 1997, all with cold ironing capabilities. POSCO Pittsburg is the only place where they receive shore power. The first ship connected to shore power at the POSCO Pittsburg berth in 1991. The ships typically have a capacity of 38 000 t and are about 180 m long. Shore power is transmitted by two 440-V cables. The total circuit is limited by an 800-A breaker, which limits the load to about 0.5 MW. The ships have an average of 48 h in berth per visit. After a ship docks, two ship crewmembers pull the power cables on board, attach them to the ship's circuits, and test the polarity. The POSCO terminal operator activates the circuit upon request by the ship operator. It takes three people up to 20 min to complete the process. According to the operator, the power is synchronized without a blackout occurring.

Fig. 1. 6.6-kV connection to shoreside power at POLA.

C. Ferry Ships at Port of Gothenburg

The Port of Gothenburg has two passenger and roll-on/roll-off ferry terminals equipped with electric connections for cold ironing. The ships at the terminals have assigned locations and run on regular scheduled routes. The system has operated since the year 2000 without problems. It utilizes a 10-kV cable and transforms the electricity onboard to 400-V dc. Shore power is supplied by local surplus wind generated power. Terminal operators make the power connections and disconnections. It takes less than 10 min to complete the process. Ships' hoteling power demand ranges from 1 to 1.5 MW. Moreover, at current electricity price levels, the onshore electricity is reportedly less expensive than the electricity generation onboard. The Port of Gothenburg believes that more ship operators would retrofit their ships if more ports would offer a standardized onshore electrical connection. Different electrical voltage, frequency, and safety issues pose challenges to the cold ironing concept. It should be noted that ferry ships receive shore power only for lighting and ventilation purposes. In addition, ferry ships have no cargo moving machinery and have little dockside activities. Therefore, the Gothenburg electrification process is much simpler than oceangoing cargo ships.

D. China Shipping Terminal at the POLA

The POLA completed an AMP project at the China Shipping terminal, at Berths 97–109. The terminal was retrofitted with conduit, wiring, and a transformer. The Los Angles Department of Water and Power (LADWP) and POLA have standardized the shoreside part of the system. LADWP input is at 14.5 kV, which is stepped down to 6.6 kV and provided to cargo ships.

For ships using 440 V, another step-down transformer could be placed on shore, on a barge, or on the receiving ship. LADWP has stated that there is sufficient system capacity for providing the power for shoreside electrification without the need for developing new supplies (Fig. 1).

E. U.S. Navy

The U.S. Navy generally cold irons its ships at its stations. Most of the U.S. Navy ships are built with cold ironing connectors, breakers, and controls, and most U.S. Naval stations have the electrified infrastructure to provide the power. The shore power is usually supplied from 450-V shore transformer and connected to the ship by multiple of 400-A plug, receptacles, and flexible cable. It should be noted that most naval ships have very low electrical power demand while hoteling. In contrast, an off-loading tanker requires much more power while at berth than while underway. It should also be noted that the time at berth of commercial cargo ships (ranging from 24 to 48 h) is much shorter than the extended port stay of a navy ship (weeks or even months). Having such a long time in port makes cold ironing cost-effective for the U.S. Navy.

III. Cold Ironing Challenges

The viability of cold ironing applications and their ability to power ships at dock depends greatly on the infrastructure outlay. For this measure to be successful, sufficient power must be available for use at the wharves and land for substation development and cable-laying right-of-way must be available close to the terminals. In addition, some ships may not have the correct electrical hookups to allow the proper connection.

A. Shoreside Power Sources

Natural Resources Defense Council [1] recommends three specific power source options, namely: 1) a new installation or an upgraded substation; 2) fuel cell units; and 3) a "power barge."

- Installation or upgrade of a port area substation would be appropriate for terminals requiring high power loads, such as cruise terminals or very large cargo areas. Requirements would include 3- to 15-MW transformers that meet varying voltage requirements and flexible connections for ships loading or off-loading at dock. The emissions associated with the electrical generation supplied by the substation must be significantly lower than the emissions generated by auxiliary engines on the receiving ships to ensure meaningful reductions, making the use of renewable energy sources or natural gas appropriate. Any port-operated substation should employ the best available control technology to reduce pollution impacts.
- The second power generation option is the installation of one or two fuel cell units (200 to 250 kW) at berths where smaller ships (tugboats, commercial fishing boats, and crew/supply boats, for example) are hoteling and where natural gas is available as a fuel source.
- The third option is a power barge equipped with fuel cells that can maneuver within a port to supply power at multiple locations. The fuel cell application might be particularly well suited for cargo ships in berth where diesel generators producing auxiliary loads are in the 1- to 2-MW range, as opposed to cruise ships, for which the load can be an order of magnitude higher. Fuel cell technology offers many significant enhancements over existing diesel generators with respect to marine applications. These enhancements include very low exhaust emissions, inherently low vibration and sound levels, and improved thermal efficiency (particularly at low-load levels).

The U.S. Navy is one of the many navies considering the use of integrated electric plants employing fuel cells in future ship designs. However, ships employing fuel cells for propulsion are not yet commercially available. In fact, fuel cells for auxiliary power or shoreside power generation is also still in the development stage and, therefore, cannot yet compete with existing technologies on a cost basis.

The POLB study [2] assumes that power supplied by the local utility would be transmitted by new overhead lines and poles. The voltage would then be stepped down to 12.5 kV and run underground through street rights-of-way to the terminals (distribution system) where it would be metered. The 12.5-kV underground distribution into the terminals would again be reduced to 6.6 kV at an on-terminal substation and then run to the wharf.

B. Power Delivery to the Ships

In most ports, gantry cranes run the full length of the wharf to unload all the container ships, reefers, and dry bulk ships. The cranes operate on fixed rails and must have the full range of the wharf, although they typically operate at one station for an extended period before moving to the next station. Thus, no fixed electrical transfer structures can be constructed in their way, although a movable wheel-mounted system is theoretically possible. In addition, any given ship may tie up at different positions along the same berth, so that the use of a fixed point for power transfer would reduce the terminal's operational flexibility.

In [2], two different methods for transferring the power from wharf side to the ship (work-barge and cable reel towers) were evaluated. Because of the potential difficulties associated with using cable reels on the ship, a work-barge concept to transfer the power from the wharf face to the stern of the ship at centerline was found preferable. The work barge supports the final substation by providing a location to step down the 6.6 kV to the typical 440–480 V that the majority of the ships currently use.

The work barge also houses cable reels, davits, and all necessary equipment to make the temporary connections to the ships. In the event that a large container ship with a 6.6-kV system arrives, the barge can still be used to connect the ship directly to the wharf power, bypassing the onboard 6.6 kV/440 V substation. Outfitting the ships with just one or two cable reels on the deck and feeding high voltage 6.6-kV cables to the side of the wharf to be plugged into a vault was suggested.

C. Ship Modifications

Most ships currently in service are designed with a shore power capability that is only intended to support an extended berthing period. During such a time, only hotel loads and support services deemed necessary to ensure personnel safety and equipment protection are considered to be in operation. This limited capability cannot accommodate operating auxiliaries or equipment associated with cargo handling operations. Therefore, it is necessary to implement conversion of shipboard power distribution systems to permit a complete shutdown of the ship's electrical power generating plant while using shore facility power to supply all in-port electrical needs.

Switchboards should be modified in order to accept large capacity shore power feeds. This conversion will also require specific structural modifications associated with installation of the shore power receptacles, cables, and switchboard modifications.

IV. Interconnection Standards, Rules, and Regulations

There are no publications addressing interconnections of marine ships to shoreside electrical power; however, some aspects are partially covered in military and commercial specifications, standards, rules, and regulations. The applicable extracts from existing rules and regulations for the shore power and medium voltage interconnections are given as follows:

A. ABS Shore Power Requirements: ABS Steel Ship Rules—2004 Section 4-8-1 [3]

Shore Connection 4-8-2/11.1: Where arrangements are made for the supply of electricity from a source onshore or other external source, the following requirements apply.

Connection Box and Cable 4-8-2/11.1.1: A shore connection box is to be provided on the vessel for the reception of the flexible cable from an external source. Fixed cables of adequate rating are to be provided between the shore connection box and the main or emergency switchboard.

The cable is to be protected by fuses or a circuit breaker located at the connection box. Where fuses are used, a disconnecting means is also to be provided. Trailing cable is to be appropriately fixed to avoid its imposing excessive stress on the cable terminal.

Interlock Arrangements 4-8-2/11.1.2: An interlocking arrangement is to be provided between all generators, including the emergency generator, and the shore power supply to prevent the shore power from being inadvertently paralleled with the shipboard power.

Instrumentation 4-8-2/11.1.3: An indicator light is to be provided at the main or emergency switchboard to which shore power is connected to show energized status of the cable. Means are to be provided for checking the polarity (for dc) or the phase sequence (for three-phase ac) of the incoming supply in relation to the ship's system.

Earth Connection 4-8-2/11.1.4: An earth terminal is to be provided for connecting the hull to an external earth.

Information Plate 4-8-2/11.1.5: An information plate is to be provided at or near the connection box giving full information on the system of supply and the nominal voltage (and frequency if ac) of the ship's system and the recommended procedure for carrying out the connection.

B. IEEE STD-45 (2002)—Recommended Practice for Electrical Installations on Shipboard (Sponsored by Marine Subcommittee) [4]

Section 5.3 Shore Power: If a shore power connection is provided, a connection box (see 17.7) should be installed in a location convenient for the reception of the cables from the shore. The shore power system should include shore power circuit breaker(s), shore power available indicating light(s), and a phase sequence or phase rotation detection device.

Cables from the connection box to the ship service switchboard should be permanently installed. One of the switchboard voltmeters should have the capability to indicate the shore power voltage.

Section 8.9.4 Shore Power: The shore power feeder should have a circuit breaker with a pole for each ungrounded conductor installed in the switchboard for connecting power from the shore connection panel to the ship service distribution bus. An indicating light should be illuminated when power is available from shore, and one of the switchboard voltmeters should have selector switch capability to read shore power voltage.

Mechanical or electrical interlocking of the shore power circuit breaker with the generator circuit breakers should be installed unless load transfer paralleling capability is provided.

Section 17.7 Shore Connection Boxes: Shore connection boxes should comply with the following.

a) Connection boxes mounted in exposed locations on the weather deck shall have portable cable connection capability utilizing watertight multipole power receptacles or protected terminals.
b) The terminals should be properly sized and shaped to facilitate satisfactory connections.
c) There should be phase sequence marking for the terminals for three-phase ac system portable cables.
d) Terminals should be polarity marked for dc system portable cables.
e) There should be an instruction plate, or sheet, providing essential information on the ships electrical supply system and connection requirements.
f) Connection boxes should have provisions for bottom entrance of portable cables.
g) Connection boxes should be designed to prevent moisture or water entrance via the top or sides of the enclosure.

C. IEEE Industrial Standards

If ship generators ever will be used for providing emergency power to the shore loads, the following IEEE standards should be applied in full:

IEEE STD 446 (1995)—Emergency and Standby Power Systems for Industrial and Commercial Applications (orange book) [5]

IEEE STD 1547 (2003)—Interconnecting Distributed Resources with Electric Power Systems [6].

V. Challenges of Medium Voltage Shore Power

The requirements of medium voltage shore power demand new initiative in the following areas.

A. Type and Quantity of Shoreside Connections

Modern container ship operations at berth present many challenges when connecting shore power to the ships. Wharf space is limited and container cranes operate near the edge of the wharf.

Shoreside connections need to be located away from cranes at the edge of the wharf at locations flexible enough to accommodate different ships at berth.

B. Type of Shoreside Power

If ships are retrofitted for the connection to shore power, standards are needed to simplify connection methods and establish voltage level and connection ampacity.

If a plug/receptacle connection is used for shore power connections, an international standard for compatibility should be developed to allow ships to connect at different ports throughout the world.

Likewise, standards need to be developed to identify acceptable ranges for shoreside voltage level and system frequency.

C. Type of Medium Voltage Protection in the Shoreside Switchgear

Shoreside switchgear protection schemes must be coordinated with shipboard switchgear. A standard protection scheme should be used to accommodate different ships using the same berth.

Interlocking systems should be designed for connections to be made while both shore and ship systems are deenergized. The type of interlocking, i.e., ground check conductor or key interlocking, should be standardized to ensure compatibility and personnel safety.

Personnel safety systems will need to be designed to ensure the safety of dock workers and personnel making connections. The medium voltage connection points will need to be accessible but well protected from possible abuse from operations on the wharf.

D. Medium Voltage Cables Connecting Ship to Shore

A standard should be developed to identify appropriate cable types for connecting ships to shore. Cables need to be flexible and be suitable for the marine environment. Cables are also subject to tension at times. Commercial ships can be fitted with cable managers to reel down cable to wharf connection points. The cable managers can be fitted with tension sensors to trip the circuit when allowable tensions are exceeded.

VI. Conclusion and Recommendations

Environmental groups and concern over emissions while ships are docked are forcing commercial ports to provide shore power systems for commercial ships at berth.

Current rules and standards need to be revised, and new ones need to be developed to ensure systems are compatible at ports around the world.

Ship designers, shippers, and port authorities should be involved in the development of these standards to ensure safe cost-effective methods are developed for powering ships on shore power.

The authors would like to recommend the following actions to the IEEE Marine Industries Subcommittee.

1) Create a working group to study and to develop recommendations for appropriate medium voltages, frequencies, and load requirements for onshore power systems, which are considered safe, portable, and acceptable around the world.
2) Create a working group to review existing rules and standards on cold ironing and to identify requirements for onshore and onboard switchgear harmonized with international regulators for their certification.
3) Add a cold ironing chapter to the IEEE Std. 45 Recommended Practice for Electrical Installation on Shipboard.

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