Shore Charging for Plug-In Battery-Powered Ships

Power system architecture, infrastructure, and control.

By Siamak Karimi, Mehdi Zadeh, and Jon Are Suul

THIS ARTICLE REVIEWS THE AVAILABLE systems for shore-to-ship high-power charging, including recent technologies, control methods, and related challenges. The battery charging path from shore to the onboard battery involves several main components and control functions, such as power electronics converters, transformers and passive elements, plugs and interconnectors, as well as charging energy management system (EMS). A comparison of different charging systems, such as ac, dc, and wireless solutions, and the applicability of each system are discussed. Furthermore, the recent commercial shore-to-ship interfaces for charging purposes are introduced. Finally, a generic overview of the control functions needed for shore charging is provided.

BATTERY©ISTOCKPHOTO.COM/ALBERT84

Electrification of Marine Vessels and Battery Charging from Shore

The electrification of marine vessels to increase functionality, flexibility, and fuel efficiency has been evolving over several decades. The development toward electrification is also currently among the most promising options for moving toward zero-emission sea transportation. The main types of electrified propulsion systems include traditional diesel–electric solutions, hybrid systems with onboard energy storage, and fully battery-electric propulsion systems. For hybrid and battery-electric systems, onboard energy storage

Digital Object Identifier 10.1109/MELE.2020.3005699
Date of current version: 2 September 2020

2325-5897/20©2020IEEE

technologies are utilized for reducing or eliminating the fossil fuel consumption. However, applications of large-scale electric energy storage in high-power marine vessels are still facing significant challenges due to the low-energy density and high cost of batteries. Thus, the available range for pure battery-electric operation is limited, and most vessels with purely battery-based propulsion are currently short-distance ferries or vessels for local coastal transportation.

Most countries with long coastlines are currently planning for significant emission reductions along their coasts and at their ports, leading to the development of plug-in battery-powered vessels for short-sea shipping and extension of required infrastructures such as shore charging stations. The International Maritime Organization recommends the development of charging infrastructures, in particular from renewable energy sources, to facilitate the reduction in the greenhouse gas (GHG) emissions from shipping. Especially for emission controlled areas, regulations are introduced to cut emission of GHGs and particulate matters. Hence, several developments in the same direction are emerging globally, and numerous manufacturers and operators in the maritime industry are considering transitioning to clean energy alternatives.

Most countries with long coastlines are currently planning for significant emission reductions along their coasts and at their ports.

In Norway, significant governmental incentives and corresponding industrial development efforts have been recently dedicated to reduce emissions from domestic marine transportation. It is a specific focus in Norway to cut the emissions in its world heritage fjords, as recognized by the UNESCO, pushing for zero-emission vessels for passenger and car transportation across the fjords. Norway is, therefore, at the forefront of electrification of ferries and other vessels for short-distance transportation. As an example, it is expected that Norway will have 70 battery-electric ferries by 2022. Moreover, around 98% of generated electricity comes from renewable energy sources, mostly hydropower, and charging from shore is therefore providing green electric energy to the onboard batteries.

According to DNV GL's Alternative Fuel Insights, there are roughly 360 vessels with onboard battery installations operating and on order by early 2020. Of these vessels, approximately 50% have fully battery-electric or plug-in hybrid propulsion systems, with the majority being passenger or car ferries and cruise ships. Ferries are mostly used for transferring people or cars for a short distance according to a fixed schedule. For instance, MF *Tycho Brahe* and MS *Aurora*, two sister hybrid electric vessels from HH Ferries, are operating in a 4-km route between Helsingør, Denmark, and Helsingborg, Sweden, carrying up to 1,250 passengers, 260 trucks, and 240 cars. These ferries are recharged when they are docked, waiting for loading and unloading, and the charging time is about 5 min 30 s at Helsingør and 9 min at Helsingborg. When the charging time is limited by a strict schedule, the docking time must be efficiently utilized, explaining the need for fast charging. This type of charging is called *opportunity charging* since it is limited to the time when the vessel is available at the dock. However, for big cruise ships, the charging time typically varies from a couple hours to 8 h. The *Color Hybrid*, which is a big hybrid cruise vessel transferring up to 2,000 people between Sandefjord, Norway, and Strömstad, Sweden, is a good example of a plug-in hybrid cruise ship.

An overview of some relevant examples of recent vessels with plug-in hybrid or fully battery-electric power systems is listed in Table 1. In the column on the charging time, there are two main types of charging, long-term/overnight charging and/or opportunity charging in a short time when the vessel is loading or unloading. Regarding expected future developments, the Norwegian Ministry of Climate and Environment has set as an objective to achieve zero emissions operation of all ferries in Norway by 2030, which includes about 200 vessels operating across 130 routes. Furthermore, Amsterdam, The Netherlands, wants to ban all diesel-powered passenger ships and ferries from city canals by 2025. In the United States, Washington State Ferries is also proposing the addition of 16 hybrid-electric vessels to its fleet as part of its 2040 long-range plan, retiring and replacing 13 of the 23 ships currently in operation. Thus, in the coming years, a significant number of newly built vessels or retrofit installations can be expected within the full range of ferry applications listed in Table 1. Furthermore, additional efforts toward electrification of other types of vessels are also expected.

It should also be mentioned that technology for long-term power supply from shore to other types of vessels has been developed and studied for several decades. For instance, supplying the auxiliary loads of ships at berth from the onshore grid (usually referred to as "cold ironing") has been considered for a long time as an alternative to the use of auxiliary onboard (diesel) generators. Indeed, stopping all fossil-fuel-based onboard power generation helps to make the harbor area cleaner and reduces noise of diesel generators. Therefore, facilitation of power supply at ports for cold ironing and charging is turning into a requirement for future harbors. Consequently, further research is necessary for investigating loading strategies under constrained harbor environments, stability control methods, and renewable energy integration issues at future smart ports.

TABLE 1. A list of recent plug-in marine vessels.

Name	Type	Commissioning Year	Route	Charging Time	Battery Capacity	Charging Power	Comments
MV *Hallaig*	Hybrid ferry	2012	Skye and Raasay, Scotland.	Overnight	2 × 350 kWh	50 kw	• the world's first diesel-electric plug-in hybrid ferry
MF *Ampere*	All-electric ferry	2015	Sognefjord between Lavik and Oppedal, Norway.	10 min and overnight	1,040 kWh	1.2 MW 1,250–1,650 A	• the world's first all-electric car ferry • 350 passengers and 120 cars • 34 trips per day
MF *Folgefonn*	Hybrid ferry	2015	Jektevik–Nordhuglo–Hordnanes, Norway.	4 min at shortest stop, one longer charging period of 20–25 min	1,000 kWh	1 MW	• Norway's first plug-in-hybrid vessel • first inductive short-to-ship charging demonstration from 2017 to 2019 • demonstration vessel no longer in service
Vision of the Fjords	Hybrid ferry	2016	Nærøyfjord, Norway.	N/A	600 kWh	1.2 MW at 400 V	• 400 passengers
MF *Elektra*	Hybrid ferry	2017	Nauvo and Parainen, Finland	5 min 30 s and overnight	1 MWh	N/A	• 375 passengers and 90 cars • 25 trips per day
MF *Gloppefjord* and MF *Eidsfjord**	Hybrid ferry	2017	Lote and Anda, Norway.	6–7 min and overnight	2 × 540 kWh	1,500 kW	• the main power source is battery • 349 passengers
MF *Tycho Brahe* and MS *Aurora**	Hybrid ferry	2017	Helsingør, Denmark, and Helsingborg, Sweden.	5 min 30 s at Helsingør 9 min at Helsingborg	4,160 kWh	10.5 MW at 10 kV	• 1,250 passengers and either 260 trucks, 240 cars, or nine passenger train coaches
Future of the Fjords	All-electric catamaran	2018	Nærøyfjord, Norway.	20 min	1,800 kWh	2.4 MW at 1 kV	• 400 passengers • dc charging solution
MS *Color Hybrid*	Hybrid cruise	2019	Sandefjord, Norway, and Strömstad, Swe-den.	25 min at lunch stop and overnight	5,000 kWh	7 MW	• 2,000 passengers and 500 cars
Ellen	All-electric ferry	2019	Fynshav and Søby, Denmark.	20 min and overnight	4.3 MWh	4 MW at 1,000 V	• the world's largest all-electric ferry • 198 passengers and 31 cars or five trucks • dc charging connection • 40 km between charges • five or seven trips per day
Go Vakker Elen	All-electric ferry	2019	Fredrikstad, Norway	112 s	N/A	80 kW	• 24/7 operation • up to 50 passengers • inductive charging

N/A: not available.
* Sister ferries.

Power System Architecture for Charging Systems

From a power system point of view, solutions for supplying power from shore consist of an interface to the main grid by a step-down transformer, possibly an onshore energy storage system typically based on Li-ion batteries, power electronics converters responsible for ac–dc and dc–dc conversion, transformers for maintaining the galvanic isolation as well as voltage-level adjustment, circuit breakers, and cable management systems. In this article, the current shore-to-ship charging technologies are categorized into 1) conductive or wired charging systems, 2) wireless charging systems, and 3) battery-swapping mechanisms.

Wired Charging Systems

Depending on the electrical connection between shore and ship, wired charging solutions are categorized into two types of charging systems: 1) ac charging systems and 2) dc charging systems. The first evaluated shore-to-ship charging topology is based on ac charging, with all energy transferred to the ship by an ac connection. Thus, the ac–dc converter responsible for charging is placed onboard, in a similar way as for onboard electric vehicle (EV) chargers. For small battery-driven fishing and leisure boats, charging from a standard 3-phase 400-V ac plug is the most common solution for shore charging because it is commonly available in industrial environments. As a result, fishermen's and sailors' routes would not be limited due to the availability of charging options. However, for passenger or car ferries, which require more power to recharge their onboard batteries, a dedicated infrastructure should be established. Depending on the number of vessels stopping at a port and their onboard battery capacity, the required power rating of the port infrastructure may change.

Figure 1(a) shows an ac shore charging power system connecting to a single-bus dc hybrid onboard power system. Although most practical propulsion systems for ferries and larger vessels are designed to ensure redundancy by having two or more buses operating in parallel, only a single bus is shown for simplicity. Besides the grid interface, there is a stationary battery storage system, which is typically charged slowly from the grid. Overnight charging and/or charging during off-peak hours can be considered not only to decrease the stress on the local grid but also to utilize cheaper electricity. Transformer T12 is a 50-Hz transformer stepping down the grid voltage into shore bus voltage and galvanically isolating the shore bus from grid. Converter C15 serves as a charger that is responsible for rectifying received energy from shore. Converter C12, which is directly connected to onboard battery B11, controls the transferred power during the charging and discharging process. Similarly, converter C17 controls the power of the onshore battery B12. Further, converter C16 operates as a rectifier during onshore battery charging and as an inverter during onboard battery charging. It is worth mentioning that, to minimize costs, the battery pack in some onboard propulsion systems is directly connected to the main bus without a dc–dc converter. In that case, C15 controls the charging power. However, for multibus propulsion systems, there should be a dedicated charging converter like C15 for each bus, which controls the charging power balance of each onboard battery pack.

In Figure 1(b), the shore charging power system is the same as that in Figure 1(a), but it is connected to an ac-based propulsion system. For an ac charging solution of an ac-based propulsion system, it would be necessary to synchronize the voltage, phase, and frequency of the onboard power system to the onshore grid before connection to avoid severe inrush currents. The only exception would be if the onboard power system is completely passive (with zero voltage) before connecting to the onshore system. Given the time-consuming synchronization process, considering ac charging for an ac-coupled onboard system may not be a proper solution for fast charging within the critical charging time. Instead, such solutions are mostly used for cold ironing, where there are no strict time limits for connection. However, to avoid the synchronization effort, a dedicated active or passive rectifier, C27, can be employed instead of converter C21. Regarding the system in Figure 1(b), there may be an onboard transformer to provide galvanic isolation or adjust the voltage between the main ac grid and shore bus. On the other hand, adding an onboard transformer would result in higher costs and lower energy efficiency. Thus, the use of an onboard transformer will usually depend on application-specific tradeoffs.

In general, the main battery charger can be installed onboard or can be located offboard, in a dedicated charging station. Although onboard chargers make it easy to charge using a regular ac plug everywhere, there would be several limitations for the size, weight, and cost of the onboard equipment, resulting in a constraint on charging power. In contrast, dedicated offboard charging stations can provide high power for charging since the weight and the size of the charger are not limited, enabling fast charging and reduced charging time. In marine vessels, there can be size and weight restrictions in the design, such as weight- and volume-sensitive ships. For instance, this would be the case of high-speed ferries where the weight of onboard equipment can highly affect the operation range and the performance of the vessel. Hence, eliminating an onboard transformer or minimizing onboard power conversion stages can be important when moving to more efficient zero-emission sea transportation.

Figure 2(a) depicts a dc shore charging power system connected to a dc hybrid onboard power system. Comparing the power converters in Figure 1(a) with those in Figure 2(a), it is obvious that the C15 onboard is exchanged with the converter C35 onshore. However, they do not necessarily have similar ratings, so their respective cost and efficiency can differ. In this scheme, the charger converter (C32) can be removed, so the onboard battery pack is directly connected to the main dc bus. Then, an onshore dc–dc converter can be directly connected to the plug and used for controlling the charging power. This may result in weight-saving onboard the ship. Figure 2(b) depicts a dc shore charging solution for an ac-based hybrid propulsion system. The to-ship bus is connected to the input of converter C42, so the charging path is the same as that in Figure 2(a).

Wireless Charging Systems

Wireless or contactless power transfer has received great attention for EV chargers, medical applications, and consumer electronics. There are two types of wireless power transfer—capacitive and inductive—where the energy

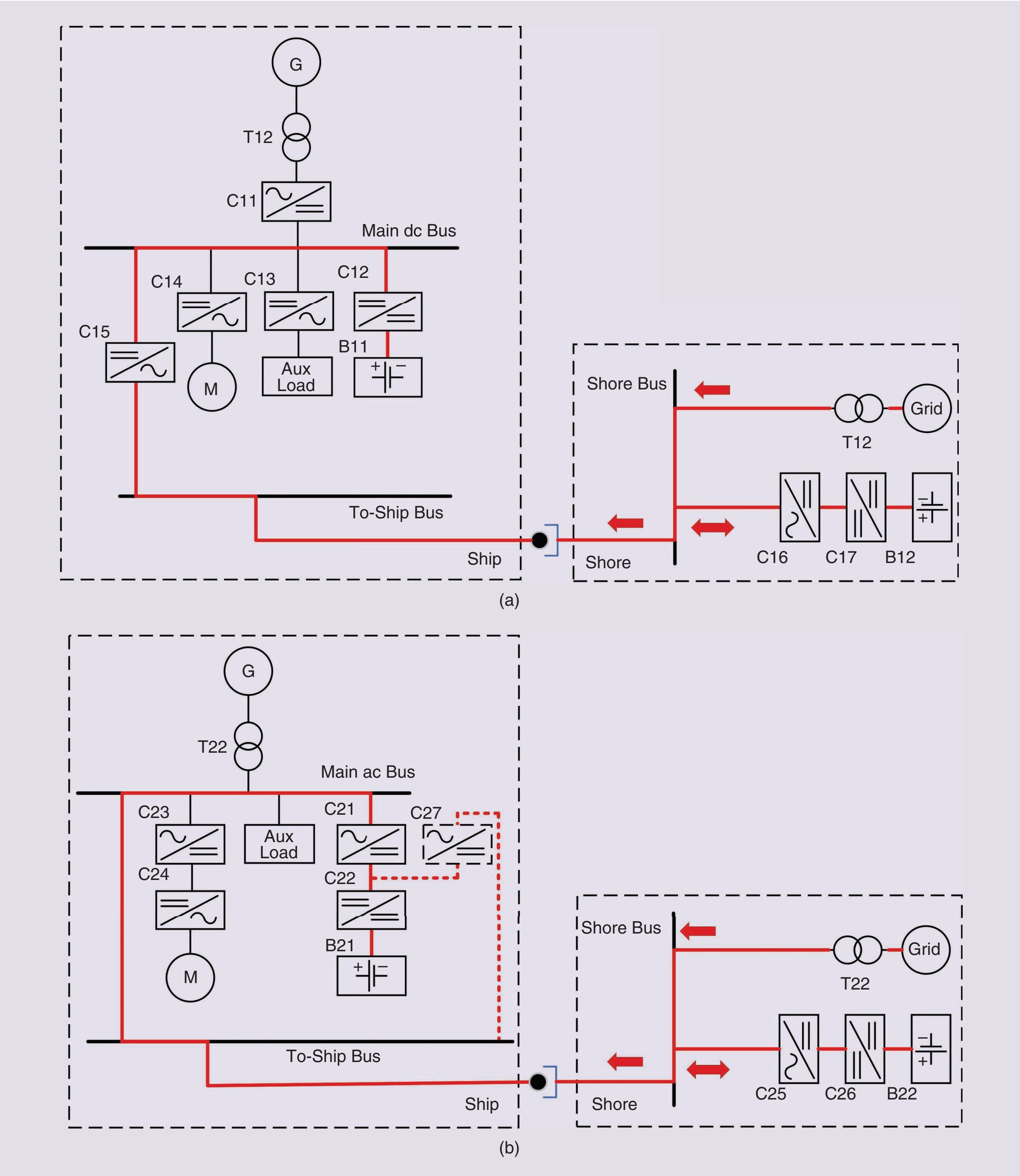


Figure 1. AC shore-to-ship charging for (a) a dc-based propulsion system and (b) an ac-based propulsion system. Aux: auxiliary; G: generator; M: motor.

transfer is based on either an electric field or a magnetic field between two plates or coils, with one operating as a transmitter and the other as a receiver. However, for high-power battery charging in electrified transportation systems, most of the research and applications have been based on inductive power transfer in which the energy is transferred through an electromagnetic field. In marine application, using wireless power transfer technology for shore-to-ship charging is promising. In harsh environments with salt water, cables and plugs are exposed to mechanical wear and tear as well as corrosion, leading to additional maintenance requirements and safety issues. By replacing plugs, receptacles, and dynamic cables with a set of coils for inductive power transfer, wireless charging can gain significant advantages over wired solutions by eliminating those issues. For opportunity charging of

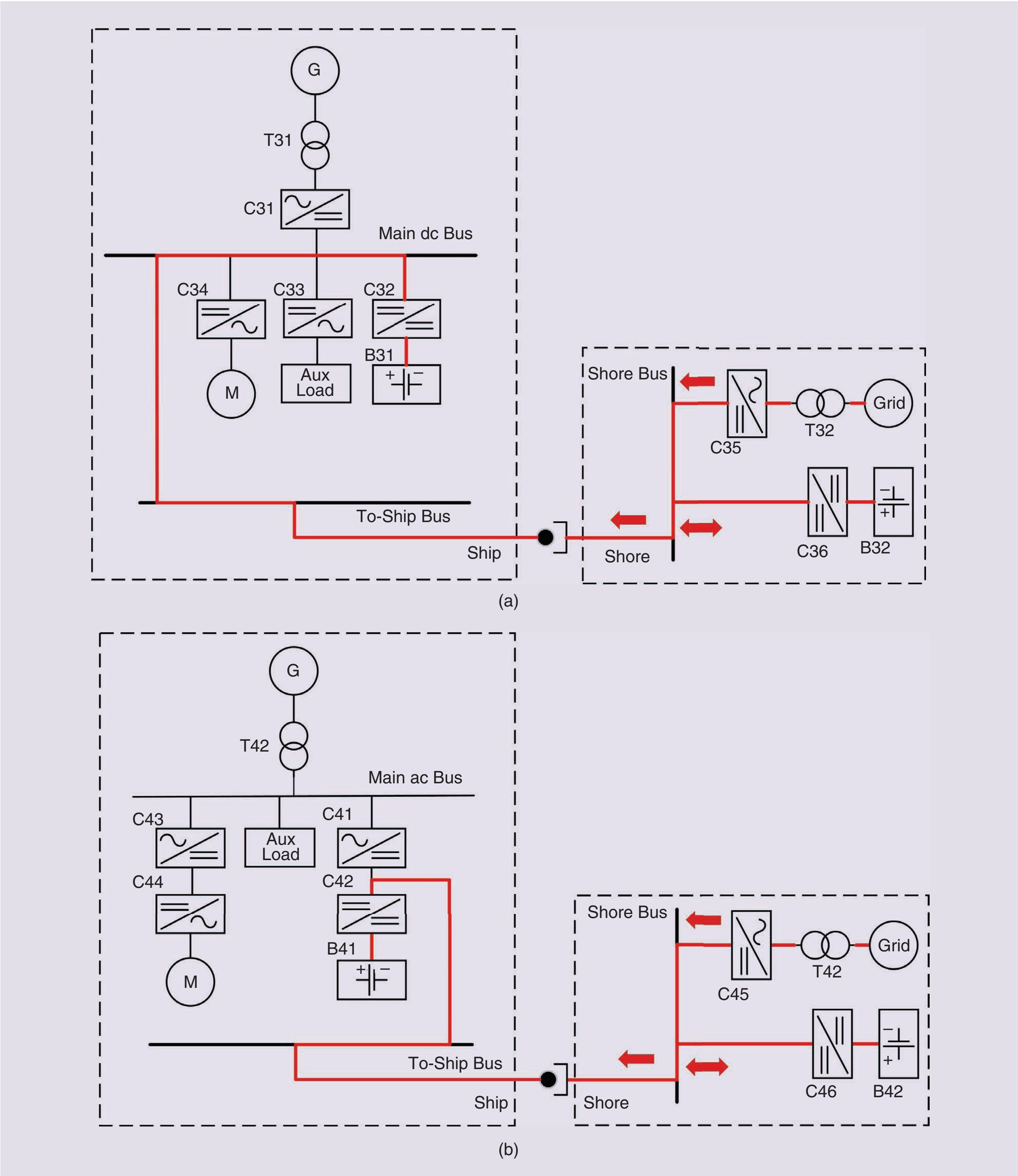


Figure 2. DC shore-to-ship charging for (a) a dc-based propulsion system and (b) an ac-based propulsion system.

scheduled ferries, in which charging time is critical, wireless charging also eliminates the need for connecting and disconnecting plugs and receptacles, making the best use of docking time to charge the batteries. In fact, the charging can be started as soon as the receiver side on the ship is close enough to the sender side on shore. A simplified model of an inductive charging for a ship with a dc main bus is shown in Figure 3.

In inductive power transfer, transmitter and receiver coils act like a transformer with a low mutual inductance. The relatively low magnetic coupling results in a high magnetizing current, so capacitive compensation networks (P51 and P52 for the example of series–series compensation in Figure 3) are used for generating the reactive power consumed by the coils. Converter C56 generates a high-frequency (several kilohertz) square-wave voltage for the transmitter coil and C55 rectifies the high-frequency output of the receiver coil. It is worth mentioning that, for C56 and C55, a two-level voltage source converter and a diode rectifier, respectively, can be used. Thus, similar converter designs like conventional ac–dc or dc–dc conversion can be utilized, although the control strategy differs from the other topologies.

As can be seen, transmitter and receiver coils provide galvanic isolation, obviating the need for a dedicated onboard transformer. All in all, the inductive charging system offers unparalleled advantages in terms of utilization of the docking time for charging, especially in situations where vessels are frequently berthed for short periods. Further, because of enhanced available charging time in wireless charging, the required power level for charging would decrease, which will also help to limit infrastructure costs. Although inductive charging offers unique benefits, it poses a few challenges, for instance with respect to cost and onboard weight. Furthermore, the achievable transfer efficiency is sensitive to the transmission distance and the requirements for maintaining power transfer capability under misalignment. Increasing the transmission frequency and/or coil dimensions can improve the efficiency of the power transfer. However, increased coil dimensions will increase the weight and volume, while challenges with losses and thermal management limit the potential for increasing power density by increasing the operating frequency.

Battery-Swapping Methods

Replacing batteries has been considered as a rapid battery refueling method, especially for electric heavy-duty trucks and electric buses. It can be a suitable solution for short-distance ferries, which have a critical docking time. In this method, discharged onboard batteries are exchanged with fully charged batteries while the vessel is at berth. Regarding the power grid, the battery-swapping solution can reduce the adverse impacts of charging stations on the local power grid since onshore battery packs are not being charged in a short time, rather they can be charged at off-peak times with cheaper electricity or transferred to a central station that may incorporate renewable energy resources (e.g., solar, wind, and hydropower energies). In other words, by using such a method, a peak load caused by charging for a short time can be distributed into a

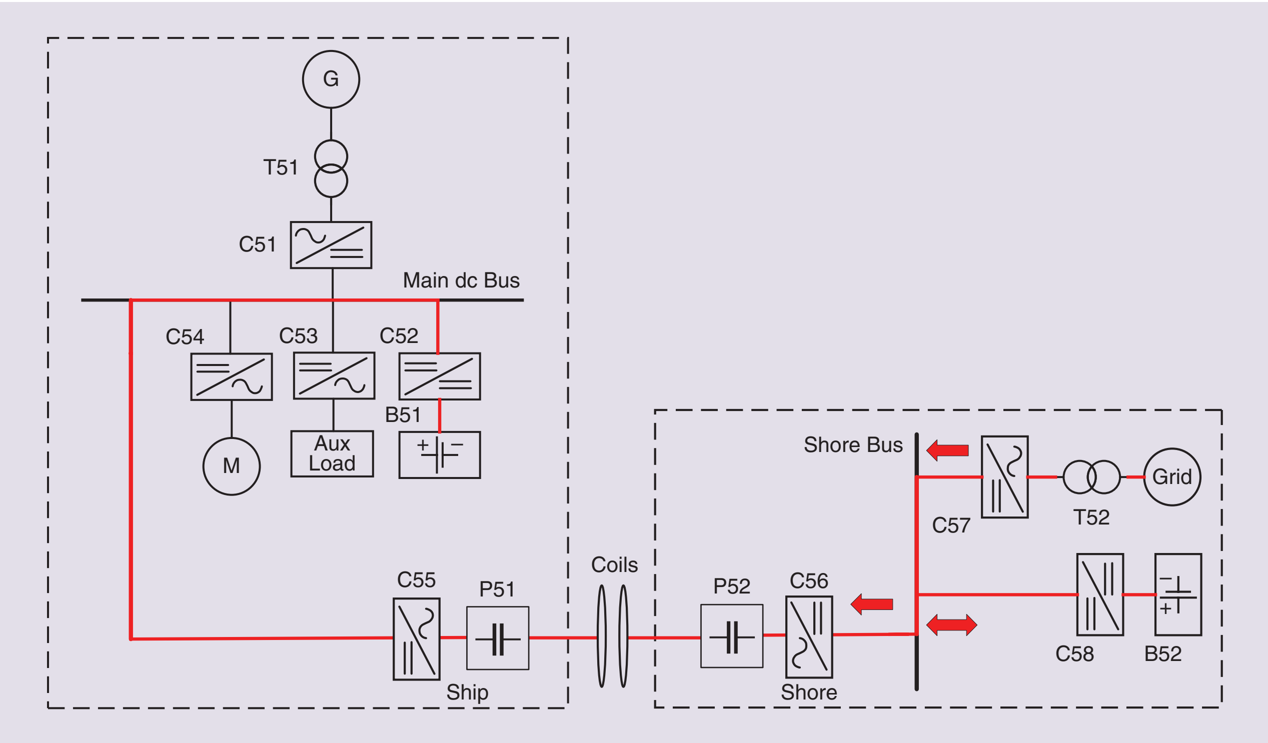


Figure 3. Inductive shore-to-ship charging for a dc-based propulsion system.

flexible and smooth load profile. Further, it is usually not required to use high-power converters for fast charging because the charging process for stationary battery packs can be carried out overnight or in several hours. However, depending on the type and application of the vessel—if a battery is discharged in a certain time, another battery would have to be fully charged in the same time, otherwise it would be necessary with multiple units.

Although battery-exchange technology offers several benefits, it may require large robotic equipment to perform the exchange process and extra battery packs onshore (for example, large cranes for moving battery packs). Hence, the excessive capital expenditures from having extra battery packs and mechanical infrastructures must be evaluated against the possible advantages of this solution, two of which are quick refueling and being less harmful to the local power grid. Figure 4 depicts the power system of a battery-swapping method. When the vessel is docked, B51, a discharged battery pack, would get substituted by B52, a fully charged battery pack.

Shore-to-Ship Interface

The shore-to-ship interface is referring to the part that enables the electric connection between the onshore and onboard power systems to transfer the electric power. This interface may include several main elements, such as electric connection, mechanical structures (e.g., robotic arms, pantograph, and towers), and monitoring systems. The electric connection could be established through either a wired link, such as plugs and receptacles, or a wireless link, like a pair of transmitter and receiver coils. When looking at previous shore-to-ship connection projects for cold ironing, most of the connection procedures were undertaken with the assistance of personnel who would carry several heavy cables, connecting, and disconnecting plugs into receptacles. This process usually takes several minutes when depending on manual actions. As can be seen in Figure 5, the connection of two cables, each of which conveys 1.2-MW charging power, is done manually. However, for ferries with short stays at berth, automatic connection systems will not only improve the safety of the system but can also maximize the time available for charging during the docking time, for instance by using a robotic arm capable of dynamic movement. Thus, automatic connection systems are needed, although they may add complexity and cost to the shore infrastructure. For long-stay vessels, the time required for connection is less critical since the connection and disconnection time will always be a small portion of the docking time. However, it can still be beneficial to utilize automatic plug systems because they provide greater safety and can operate with heavy high-voltage cables.

The NG3 PLUG is an automated shore-to-ship connector that has been used for cold ironing and charging purposes. In a typical PLUG system (Figure 6), when the ship is docked, a shuttle bar connected to a chain from

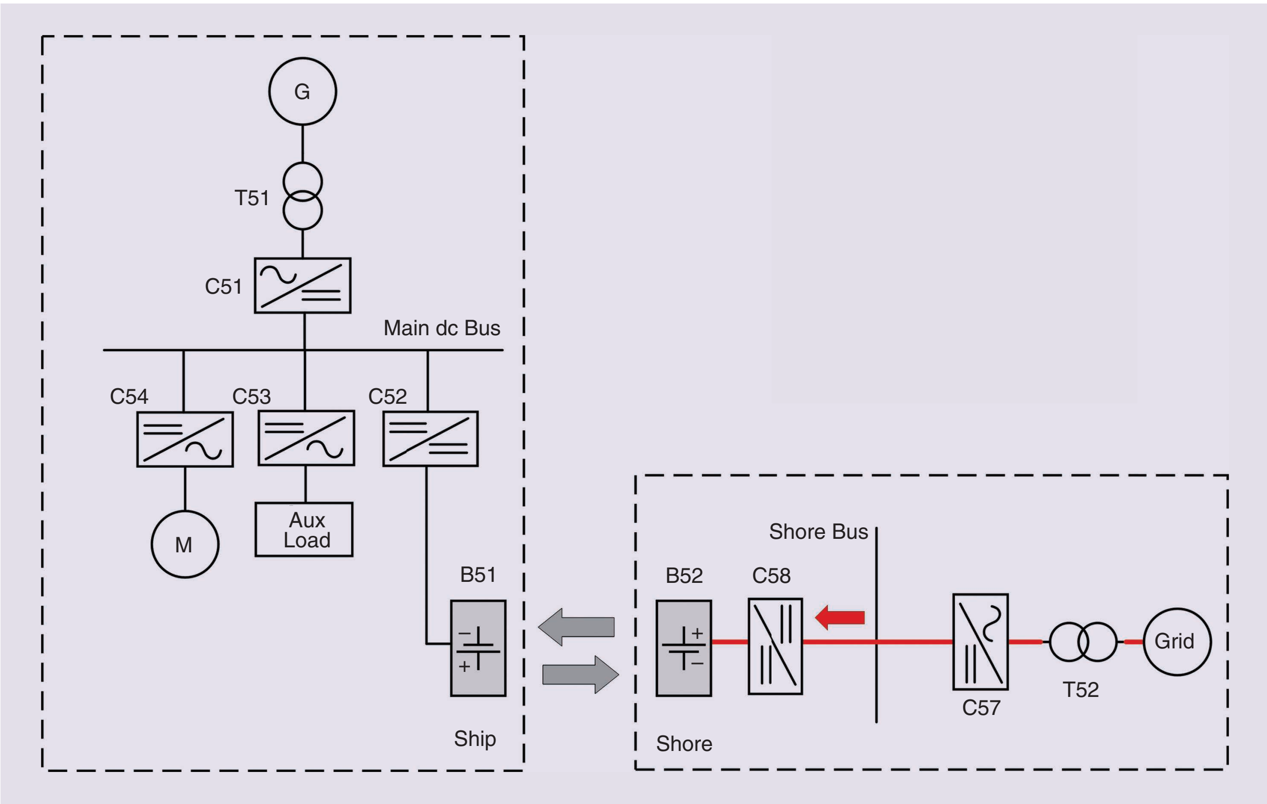


Figure 4. The battery swapping method for charging a dc-based ferry.

the ship side above the quay is lowered to reach the shore-side connector. Next, the shuttle bar is locked to the quay-side connector. Then, the chain lifts the power socket up to the ship-side socket. The NG3 PLUG is used to provide the *Color Hybrid* with 2.5-MW overnight charging and 6.5-MW afternoon-stop charging.

For the two sister ferries MS *Aurora* and MF *Tycho Brahe*, the ABB IRB7600, an autonomous robotic arm (Figure 7), is employed to automatically connect cables through a plug into the onboard charging port. It is placed on land, and the connection procedure starts by the robot turning on to be ready for initiating the mechanical connection when the ferry approaches port. It features a 3D laser positioning system for recognizing the onboard receptacles in harsh conditions.

Another plug solution, which has been used for charging MF *Ampere* and MF *Elektra*, is Cavotec's Automated

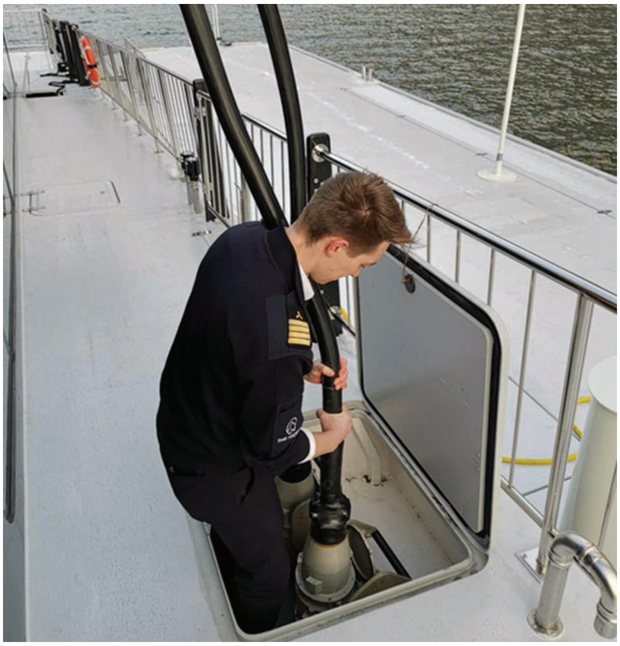
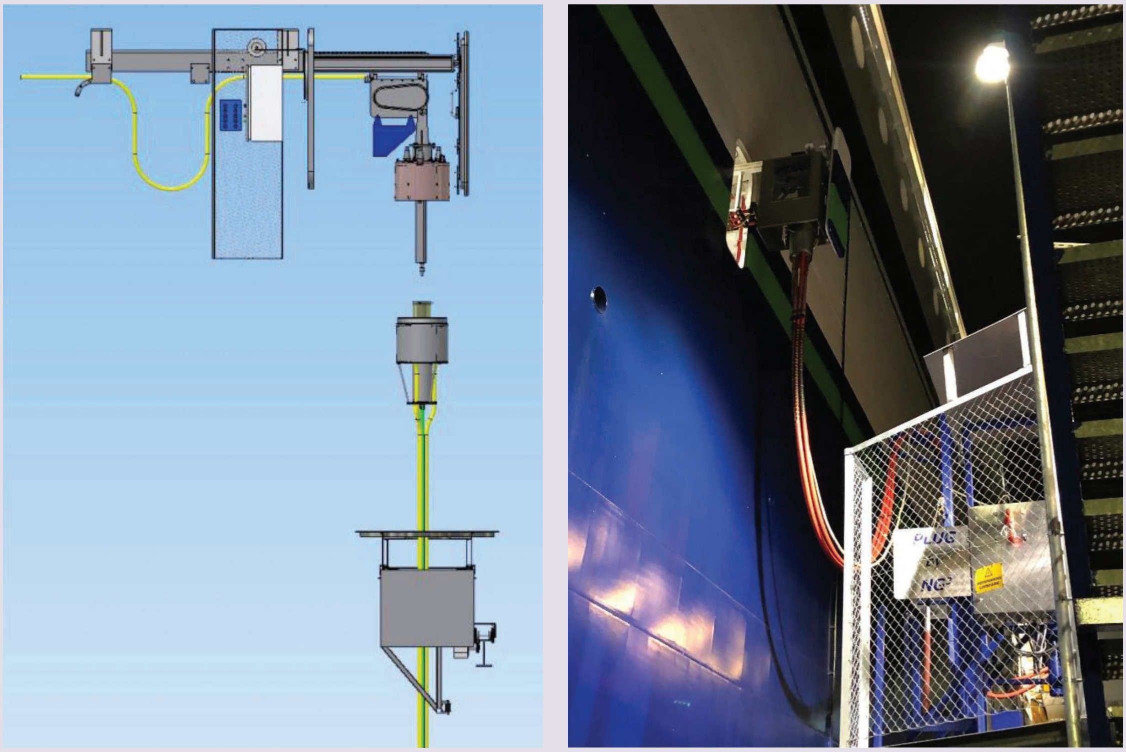


Figure 5. The manual connection of two cables for charging the future of the fjords. (Source: Severin Synnevåg; used with permission.)

Figure 7. The ABB IRB7600, an autonomous robotic arm used for charging the MS *Aurora* and MF *Tycho Brahe*. (Source: ABB; used with permission.)



(a) (b)

Figure 6. (a) The typical PLUG structure and (b) the NG3 PLUG used for charging the *Color Hybrid*. (Source: PLUG; used with permission).

Figure 8. The Cavotec Automated Plug-in System tower used for charging the MF *Elektra*. (Source: Cavotec; used with permission.)

Plug-in System (APS) tower. As shown in Figure 8, from top of the tower a plug automatically drops into the onboard receptacle, which has been exposed, enabling flexibility for low- and high-water levels. Using the automatic mechanism, the charging process can start 1 min after a ship docks. To make the ferry still and secure at berth, a vacuum mooring system is employed.

Lately, Cavotec has developed another automatic plug-in system called APS Counterweight, which is currently being installed in Oslo, Norway. As is indicated in Figure 9, this tower is applicable for ferries with charging points in the bow, aiming to reduce the size of onboard and onshore system.

The Mobimar Nectors also provide automated charging connectors for dc and ac systems; Nectors accesses the bow section for shore-to-ship connection using the existing car ramp to limit the effect of ship movements caused by sea-level changes during shore charging. This system has been used for the E-ferry *Ellen* as a 4-MW dc charging connection, as is depicted in Figure 10.

Figure 9. The Cavotec Automated Plug-in System Counterweight allows automatic connection with the charging point on ferry bow. (Source: Cavotec; used with permission.)

The Stemmann-Technik FerryCHARGER is another commercial automated contact-based charging system for battery-electric vessels, as shown in Figure 11. This system utilizes a pantograph, which is capable of moving 15 ft vertically, within the tower, and 1.3 ft horizontally. The

Figure 10. The Mobimar Nectors dc-based charging station for the E-ferry *Ellen*. (Source: Mobimar; used with permission.)

connection process is completed within 10 s, and the charging can start immediately after the contact is established. For the *Ampere*, there are two connection provided, the pantograph-based FerryCHARGER and a Cavotec APS tower similar to the system in Figure 7. The pantograph system is preferred because it is faster to connect and allows for more motion of the ferry when docked. For the plug system, the operator must wait for the arm to extend before lowering the plug. Moreover, the plug does not have much flexibility, so if the vessel moves, the plug can become loose, interrupting the charge and damaging the contacts. In addition, other than the side-mounted FerryCHARGER utilized for *Ampere*, Stemmann-Technik is offering other solutions, such as side-telescope, ramp-type, tower-type, and bow-type solutions, capable of providing several megawatts of charging power.

The Zinus ZPP850 (Figure 12) offers an automatic shore-to-ship connection with current capability of 4,500 A. It has

Figure 11. The Stemmann-Technik FerryCHARGER unit. (Source: Stemmann-Technik; used with permission.)

Figure 13. The Wärtsilä inductive charging system for charging the MF *Folgefonn*. (Source: Wärtsilä; used with permission.)

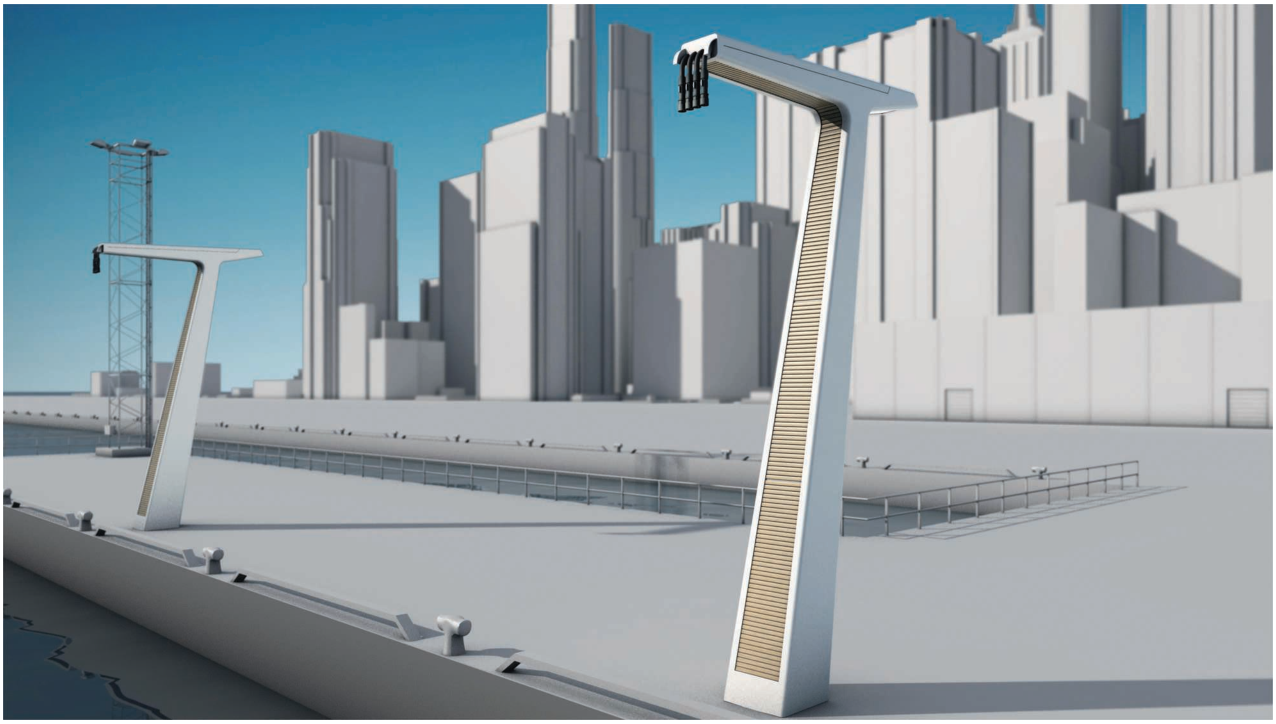


Figure 12. The Zinus port power P850 system. (Source: Zinus AS; used with permission.)

a telescopic arm capable of revolving 180° and a 10-m tidal difference adjustment, which is placed on top of a tower. The arm can feed 20-m cables into the onboard reception, which automatically pulls the charging cables into a dry and safe environment.

As mentioned, inductive charging is a promising solution for maritime applications since it eliminates the physical contact between the shore side and the ship side. There are already two examples of inductive charging infrastructures that have been demonstrated for battery-electric ferries. In Wärtsilä's inductive charging system for MF *Folgefonn* (Figure 13), a robotic arm is used for moving the onshore, transmitter coil close to the receiving coil on the ship. However, this robotic arm does not have to track the accurate position of the receiver coil onboard the vessel. Rather it is designed to compensate for the tidal movements, which can cause variances of several meters in water levels in some locations along the Norwegian coast. The robotic arm is also utilized to move the transmitter coil back into a safe position when it is not in use since other vessels may need to dock at the same position. Because the direct mechanical connection requiring accurate positioning is eliminated using inductive charging, the charging process can be started as soon as the ferry is approaching the onshore installation. By utilizing wireless communication between the ferry and the port, the onshore robot arm can be prepared to approach the receiver coil when the vessel is approaching the dock, and the power transfer can start automatically when the distance is small enough. This charging system was capable of transferring a maximum 1 MW of power in the range of 15–50 cm of distance between the coils.

Figure 14 depicts an inductive shore-to-ship charging system developed by IPT Technology for an electric shuttle ferry built by Swede Ship Marine for operation in Fredrikstad. It is operated 24/7 by only one person using a 100-kW

Figure 14. Inductive shore-to-ship charging for the *Go Vakker Elen* shuttle ferry. (Source: Swede Ship Marine; used with permission.)

automated wireless charging solution. Because this ferry operates on a river, there is no major tidal movements affecting the shore-to-ship connection, so the transmitter coils are stationary.

Control and Power Management

Generally, two levels of control can be considered in a charging system: 1) low-level control, which includes control of power converters, that is, power control and voltage control depending on the mode of operation; and 2) high-level control, which includes the power and energy management system that generates the power and voltage set points for stable and efficient operation of the power system during the charging process. It also includes the onshore and onboard battery management systems, which are responsible for estimation of the state of charge (SoC) and the state of health, thermal management, and cell balancing. In a smart charging station, the efficient control commands are issued based on the ferry schedule, onshore and onboard SoC, and local grid capacity. In this section, to illustrate the function of the control and power management in shore charging, an example of the power converter and system-level control structures for a dc shore charging system for a dc-based propulsion system is introduced and discussed.

Power Converter Control

To illustrate the power converter control, a dc charging system for a dc-based propulsion system, like the system shown in Figure 2(a), is considered. In such a system, the power converters involved in the charging path have different control objectives. At the onshore station, the grid is interfaced through a transformer and a rectifier. Converter C35 is responsible for the shore bus dc-voltage control and can provide ac side voltage control or reactive power control taking into account power quality issues for the grid. Usually, a two-level voltage source converter is selected for C35. In this regard, a common control system for the C35 is depicted in Figure 15 which includes a synchronization block (typically a phase-locked loop), a current controller [usually a proportional-integral (PI) controller], a pulsewidth modulation (PWM) generator (which generates signals for driving switches in the power converter), and outer-loop controllers for power flow or dc voltage and ac voltage or reactive power, providing the active and reactive (d- and q-axis) current references. Besides the grid interface, there is an onshore battery pack connected to the shore bus through a bidirectional dc–dc converter. There are two modes of operation for converter C36: 1) charging from the grid and 2) discharging to the ship. For Li-ion batteries, the charging process is typically started with a constant current while the battery voltage rises until the moment that the battery voltage reaches a specified value, then the charging continues with a constant

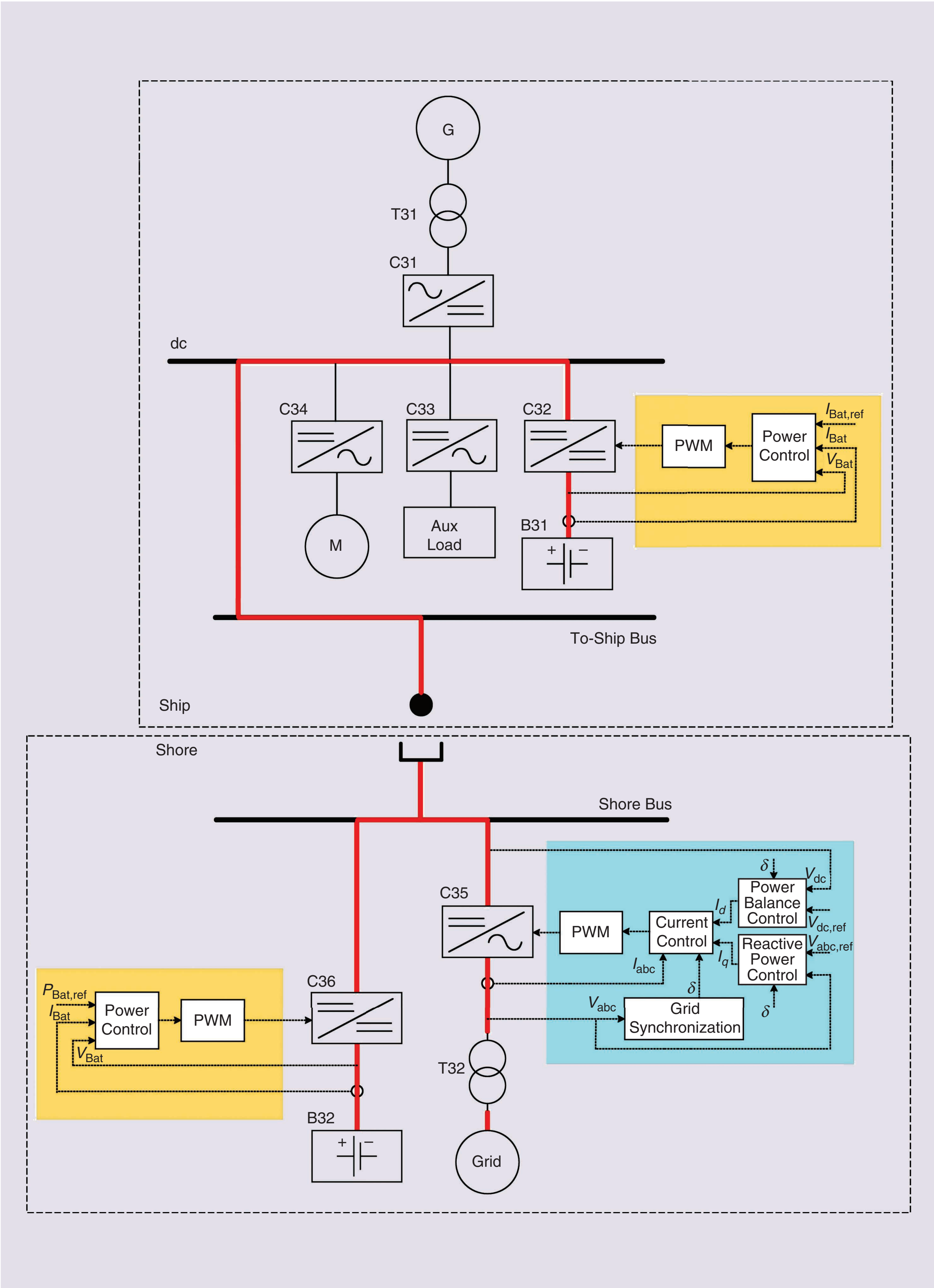


Figure 15. An example of converter-level control for dc charging applicable for a dc-based ferry.

voltage and descending current. The controller for such a dc–dc converter is comprised of a power control block, which ensures tracking the reference power and includes an inner current control loop, as well as a PWM block. Similarly, for the onboard battery pack, converter C32 controls the charging power. Thus, it regulates the charging power when the vessel is at berth and discharging power when the vessel is operating. The control mechanism can be the same as for converter C36.

Shore charging is a great opportunity to use a land-based grid supported by renewable energy systems for powering the propulsion of marine vessels.

System-Level Control

To discuss the high-level control, it is better to study the onboard and onshore controllers separately since they can be highly dependent on the type of application. An example of a high-level control scheme is depicted in Figure 16. As mentioned in the previous sections, onshore battery packs are recharged from the grid and discharged into the onboard batteries, so there are four modes of operation for a charging station: 1) charging onshore batteries when no vessel is docked, 2) when a vessel is docked; charging based only on power from the grid, 3) transferring power to the ship only from the onshore batteries, and 4) transferring power to the ship from both the grid and the onshore batteries. The onshore batteries are usually charged overnight with low power or between ferry dockings with higher power. Thus, in the charging station, an EMS and a power management system (PMS) are needed for generating the references for the total charging power, the charging and discharging power of the onshore battery bank, and the power from the grid. Apart from the power flow, controlling the voltage of the shore bus is another objective for the onshore controllers. Furthermore, a battery management system (BMS) is typically used to perform battery monitoring and battery cell balancing. The BMS communicates with the EMS to operate the battery in a safe and optimal manner.

When a ferry is at berth, onboard charging control would send the amount of required charging power, so the onshore EMS should decide the share of the grid power and the onshore battery bank. Utilizing the onshore battery reduces the stress of handling high charging power on the local grid and can allow for reducing the total electricity costs by charging during off-peak hours. On the other hand, drawing the charging power from the onshore battery bank is less energy efficient than using the grid because of the energy loss generated by the additional power electronics converters used to interface with the onshore battery and the battery itself. In other words, using energy buffers such as onshore battery packs generates additional energy loss in the process of charging and discharging the onshore batteries. Hence, the onshore EMS should choose the optimal share of sources in terms of energy transfer efficiency, power quality issues, and/or cost of energy from the grid. In a smart charging station, the information from the port substation is considered for making the decision of load sharing between onshore batteries and the grid.

For instance, assume the required charging power to be 800 kW for 10 min and that the ferry will come back at berth for the next charging after 30 min. If the charging power from the grid and the onshore battery pack are 200 kW and 600 kW, respectively, the onshore battery pack can be recharged by the constant charging power of

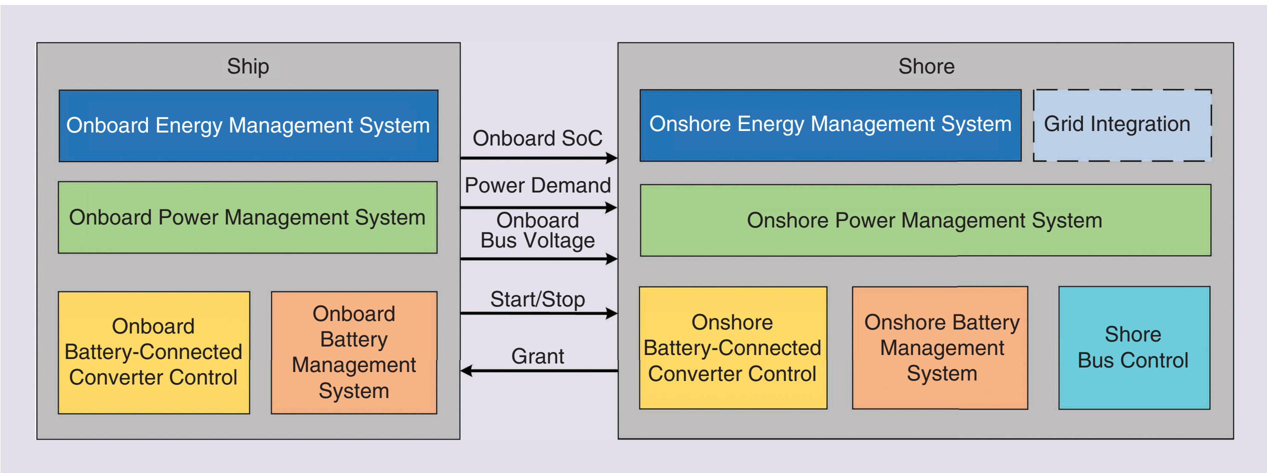


Figure 16. An example of the system-level control structure for a shore-to-ship charging system.

200 kW drawn from the gird when the ferry is away. In this case, the power drawn from the grid will be constant. However, in most practical systems, the power from the grid during charging of the onboard battery is higher than the power required for recharging the onshore battery.

For an onboard PMS, there are three states: 1) operating in all-electric mode, 2) operating in hybrid mode (or emergency mode for all-electric ferries), and 3) charging from shore. In the first mode, the converter connected to the onboard battery packs should control not only the output power of the battery but also the dc bus voltage (since no onboard generators are in operation). In the second and third modes, converter C32 is only controlling the battery power. Further, to avoid instability during the charging process in which the onboard dc bus is connected to the shore bus, two converters should not be allowed to operate simultaneously with PI dc-voltage controllers. In the case of directly connected onboard batteries, there should be a dedicated onshore dc–dc converter for controlling the charging power, making the onshore EMS and PMS more complex. During the charging process, monitoring the state of charge and voltage level of the onboard batteries as well as start and stop commands are carried out by means of the onboard PMS.

Conclusion

This article presents a review of current technologies and future trends for shore-to-ship charging of marine vessels including power system architectures, charging infrastructure, and control systems for charging management. Because the electrified vessel fleet is growing rapidly, providing cleaner energy for sea transportation from sustainable sources is a hot topic for research and development in the marine industry and academia. Shore charging is a great opportunity to use a land-based grid supported by renewable energy systems for powering the propulsion of marine vessels, although it is challenging to charge onboard batteries within a limited time from a weak grid available in remote areas.

Three methods for shore to ship charging are explained: wired charging, wireless charging, and the battery swapping method. In the wired solution, there is a plug and receptacle, which can be a pantograph or a telescopic arm, etc., to connect the shore power to the ship for charging its onboard batteries. Depending on whether the provided shore power is ac or dc, the arrangement and control objectives of power converters included in the charging path vary. In the contactless shore-to-ship connection, the electric energy is transferred through the magnetic field by two coils—the transmitter coil onshore and the receiver coil onboard. In the last method, the battery swapping method, the depleted batteries exchanged with the fully charged batteries at port. To have a better understanding of the practical solutions, some of the current shore-to-ship charging interfaces have been introduced in this article.

The control strategies used for the battery recharging process can play a significant role in energy efficiency enhancement and local grid support. In this regard, an example of a high-level and a low-level control scheme for a dc charging system was discussed in the last section. Based on current and future trends involving the shore-to-ship charging and the specification of the ship, the proper choice of power system architecture for the charging system and the control strategy plays an important role for improving the efficiency and cost of the system.

For Further Reading

P. Ghimire, D. Park, M. K. Zadeh, J. Thorstensen, and E. Pedersen, "Shipboard electric power conversion: System architecture, applications, control, and challenges," *IEEE Electrific. Mag.*, vol. 7, no. 4, pp. 6–20, Dec. 2019. doi: 10.1109/MELE.2019.2943948.

G. Guidi, J. A. Suul, F. Jenset, and I. Sorfonn, "Wireless charging for ships: High-power inductive charging for battery electric and plug-in hybrid vessels," *IEEE Electrific. Mag.*, vol. 5, no. 3, pp. 22–32, 2017. doi: 10.1109/MELE.2017.2718829.

R. Bosshard and J. W. Kolar, "Inductive power transfer for electric vehicle charging: Technical challenges and tradeoffs," *IEEE Power Electron. Mag.*, vol. 3, no. 3, pp. 22–30, Sept. 2016. doi: 10.1109/MPEL.2016.2583839.

"Wireless charging," Wartsila, Helsinki, Finland. Accessed on: Jan. 27, 2020. [Online]. Available: https://www.wartsila.com/marine/build/power-systems/shore-connections/wireless-charging

"FerryCHARGER for electric ferries," Stemmann-Technik, Schüttorf, Germany. Accessed on: Jan. 27, 2020. [Online]. Available: http://www.stemmann.com/en/products/charging_systems/ferrycharger

"E-CHARGING," Cavotec, Lugano, Switzerland. Accessed on: Jan. 27, 2020. [Online]. Available: http://www.cavotec.com/en/your-applications/ports-maritime/e-charging

M. S. Eide, "Charting a course for green coastal shipping," DNV GL, Oslo, Norway, 2016. doi: 10.13140/RG.2.2.32516.94088.

"Analysis of charging- and shore power infrastructure in Norwegian ports: ReCharge," DNV GL, Oslo, Norway. Accessed on: Jan. 27, 2020. [Online]. Available: https://www.nek.no/wp-content/uploads/2019/03/DNV-GL-2017-0101_ReCharge.pdf

T. W. P. Smith et al., *Third IMO GHG Study 2014*. London: International Maritime Organization (IMO), 2014.

Biographies

Siamak Karimi (siamak.karimi@ntnu.no) is with the Department of Marine Technology, Norwegian University of Science and Technology, Trondheim.

Mehdi Zadeh (mehdi.zadeh@ntnu.no) is with the Department of Marine Technology, Norwegian University of Science and Technology, Trondheim.

Jon Are Suul (jon.are.suul@ntnu.no) is with SINTEF Energy Research, Trondheim, Norway, and with the Department of Engineering Cybernetics, Norwegian University of Science and Technology, Trondheim.