Shore charging for plug-in battery-powered ships: power system architecture, infrastructure and control

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I. Electrification of Marine Vessels and Battery Charging from Shore

While electrification of marine vessels has been a development trend over several decades for increasing functionality and flexibility while reducing fuel consumptions, it is currently among the most promising options for moving towards 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 technologies are utilized for reducing or eliminating the fossil fuel consumption. However, applications of large-scale electrical 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 alongside the coast and at the ports, leading to 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 (IMO) also 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 the Emission Controlled Areas (ECAs), regulations are introduced to cut emission of GHGs and particulate matters. Hence, several developments in the same direction are globally emerging, and numerous manufacturers and operators in the maritime industry are considering possibilities for transitioning towards clean energy alternatives.

In Norway, significant governmental incentives and corresponding industrial development efforts have been recently dedicated towards reducing emission from domestic marine transport. It is also an especial focus in Norway to cut the emissions in Norwegian world heritage fjords recognized by 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 within 2022. Moreover, around 98 percent of generated electricity comes from renewable energies, mostly hydropower, and charging from shore is therefore providing green electrical energy to the onboard batteries.

According to DNV-GL Alternative Fuel Insights (AFI), there are roughly 360 vessels with onboard battery installations operating and in order by early 2020. Of these vessels, approximately 50 percent have fully battery-electric or plug-in hybrid propulsion systems, with the majority being passenger/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 MF Aurora, two sister hybrid electric vessels from HH ferries are operating in a 4km route between Helsingør, Denmark, and Helsingborg, Sweden, carrying up to 1250 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 and half minutes at Helsingør and 9 minutes at Helsingborg. When the charging time is limited by a strict schedule, it is clear that 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 hours. Color Hybrid, which is a big hybrid cruise vessel transferring up to 2000 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 are listed in Table 1. As can be seen from the column with 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 the expected future developments the Norwegian Ministry of Climate and Environment has set as an objective to achieve zero emission operation of all ferries in Norway within 2030, which includes around 200 vessels operating in 130 routes. Furthermore, Amsterdam wants to ban all diesel-powered passenger ships and ferries from the city canals by 2025. In United States, Washington State Ferries is also proposing to add 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, a significant number of newbuilt vessels or retrofit installations within the full range of ferry applications indicated in Table 1, as well as further efforts towards electrification of other types of vessels, can be expected in the coming years.

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

Name	Type	Year of commissioning	Route	Charging time	Battery Capacity	Charging Power	Comments
MV Hallaig	Hybrid Ferry	2012	Skye and Raasay, Scotland.	overnight	2* 350kWh	50kw	-The world's first diesel-electric plug-in hybrid ferry
MF Ampere	All-Electric Ferry	2015	Sognefjord between Lavik and Oppedal, Norway.	10 min + overnight	1040 kWh	1.2 MW 1250-1650 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 as shortest stop, one longer charging period of 20-25 min	1000 kWh	1 MW	- Norway's first plug-in-hybrid vessel -First inductive shore to ship charging from 2017 until 2019 -Demonstration vessel not in service any more
Vision of the Fjords	Hybrid Ferry	2016	Nærøyfjord, Norway.	NA	600 kWh for 3hr	1.2 MW at 400V	- 400 passengers
MF Elektra	Hybrid Ferry	2017	Nauvo and Parainen, Finland	5 and half min + overnight	1MWh	NA	- 375 passengers and 90 cars -25 trips per day
MF Gloppefjord MF Eidsfjord*	Hybrid Ferry	2017	Lote and Anda, Norway.	6-7 min + overnight	2*540 kWh	1500kW	-The main power source is the battery -349 passengers

MF Tycho Brahe MF Aurora*	Hybrid Ferry	2017	Helsingør, Denmark, and Helsingborg, Sweden.	5:30 min at Helsingør 9 min at Helsingborg	4160 kWh	10.5 MW at 10kV	- 1250 passengers, and either 260 trucks, 240 cars or 9 passenger train coaches
Future of the Fjords	All-Electric Katamaran	2018	Nærøyfjord, Norway.	20 min	1800 kWh	2.4 MW at 1kV	- 400 passengers - DC charging solution
MS Color Hybrid	Hybrid cruise	2019	Sandefjord, Norway, and Strömstad, Sweden.	25min at lunch stop + overnight	5000 kWh	7 MW	-2000 passengers and 500 cars
Ellen	All-Electric ferry	2019	Fynshav and Søby, southern Denmark.	20 min + overnight	4.3 MWh	4 MW at 1000 V	-The world's largest all-electric ferry -198 passengers and 31 cars or 5 trucks -DC charging connection -40km between charges -5 or 7 trips per day
Go Vakker Elen	All-Electric Ferry	2019	Fredrikstad, Norway	112 seconds	NA	80kW	-50 passengers -24/7 operation -Inductive charging

*sister ferries

It should also be mentioned that technology for use of power supply from shore for other types of vessels has been developed and studied for several decades. Indeed, supplying the auxiliary loads of a ship at birth from the onshore grid instead of an auxiliary (diesel) generator has been considered for long time and is usually referred to as "cold ironing". Indeed, stopping all fossil-fuel based onboard power generation helps to make the harbor area cleaner of pollution and 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.

II. Power System Architecture for Charching Systems

From a power system view, solutions for power supply from shore consist of an interface to the main grid by a step-down transformer, possibly an 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 mechanism.

A. Wired charging systems

Depending on the electric 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 fishery and leisure boats, charging from a standard 3-phase 400V AC plug is the most common solution for shore charging because it is commonly available in industrial environments. As a result, fishermen and sailors would not have limited routes to explore due to the availability of 400V AC sources. However, for passenger or car ferries which require more power to recharge their onboard batteries, an infrastructure or a dedicated substation 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.

In figure 1 (a), an AC shore charging power system connecting to a single-bus DC hybrid onboard power system is depicted. Although most practical propulsion systems for ferries and larger vessels have two or more busses 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 in order to not only decrease the stress on the local grid, but also to utilize cheaper electricity. Transformer T12 is a 50Hz transformer stepping down the grid voltage into shore bus voltage and galvanically isolating the shore bus from grid. Converter C15 serves as a charger which 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 is controlling the power of the onshore battery B12. Further, converter C16 performs as a rectifier during onshore battery charging and an inverter during onboard battery charging. It is worth mentioning that, for minimizing the cost, in some onboard propulsion systems the battery pack is directly connected to the main bus without a DC-DC converter. In that case, C15 controls the charging power, and for double bus propulsion systems there should be a dedicated charging converter as C15 for each bus, controlling the charging power balance of each onboard battery packs.

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. Regarding AC charging solution for 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, since connecting with voltages out of phase would lead to 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 synchronization effort, instead of converter C21 a dedicated active or passive rectifier, C27, can be employed. Regarding the system in Fig. 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 other hand, adding an onboard transformer would result to higher cost and lower energy efficiency, so depending on the application a tradeoff for using onboard transformer should be carried out.

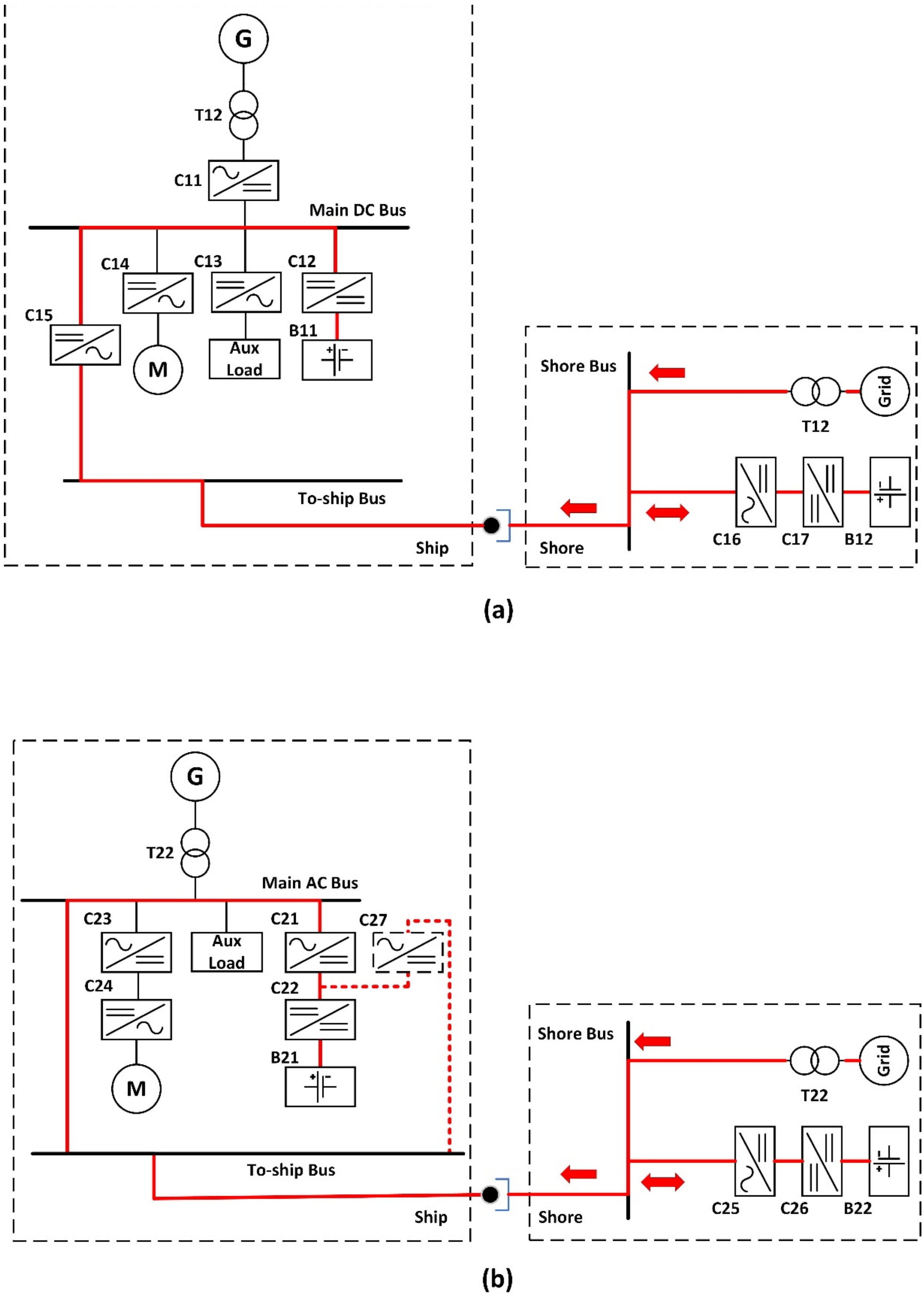


Figure 1: AC shore-to-ship charging for (a) a DC-microgrid-based and (b) an AC-microgrid-based propulsion system

In general, the main battery charger either can be installed onboard or can be located offboard, in a dedicated charging station. Although onboard chargers make it easy to charge by a regular AC plug everywhere, there would be several limitations for the size, weight and cost of the onboard equipment, resulting in a constraint for the 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 in 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 onboard transformer or minimizing onboard power conversion stages can be important when moving towards more efficient zero emission sea transportation.

Figure 2 (a) shows a DC shore charging power system connecting to a DC hybrid onboard power system. By comparing the power converters in figure 1 (a) with those in figure 2 (a), it is obvious that C15 onboard is exchanged with converter C35 onshore. However, they do not necessarily have similar ratings, so their power efficiency can be different due to use of different switches. In this scheme, the charger converter (C32) can be removed, so the onboard battery pack is directly connected to the main DC bus. Then, on shore, a DC-DC converter can be directly connected to the plug and used for controlling the charging power. It may result in a weight-saving onboard ship. In figure 2 (b) a DC shore charging solution for an AC-based hybrid propulsion system is drawn. 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).

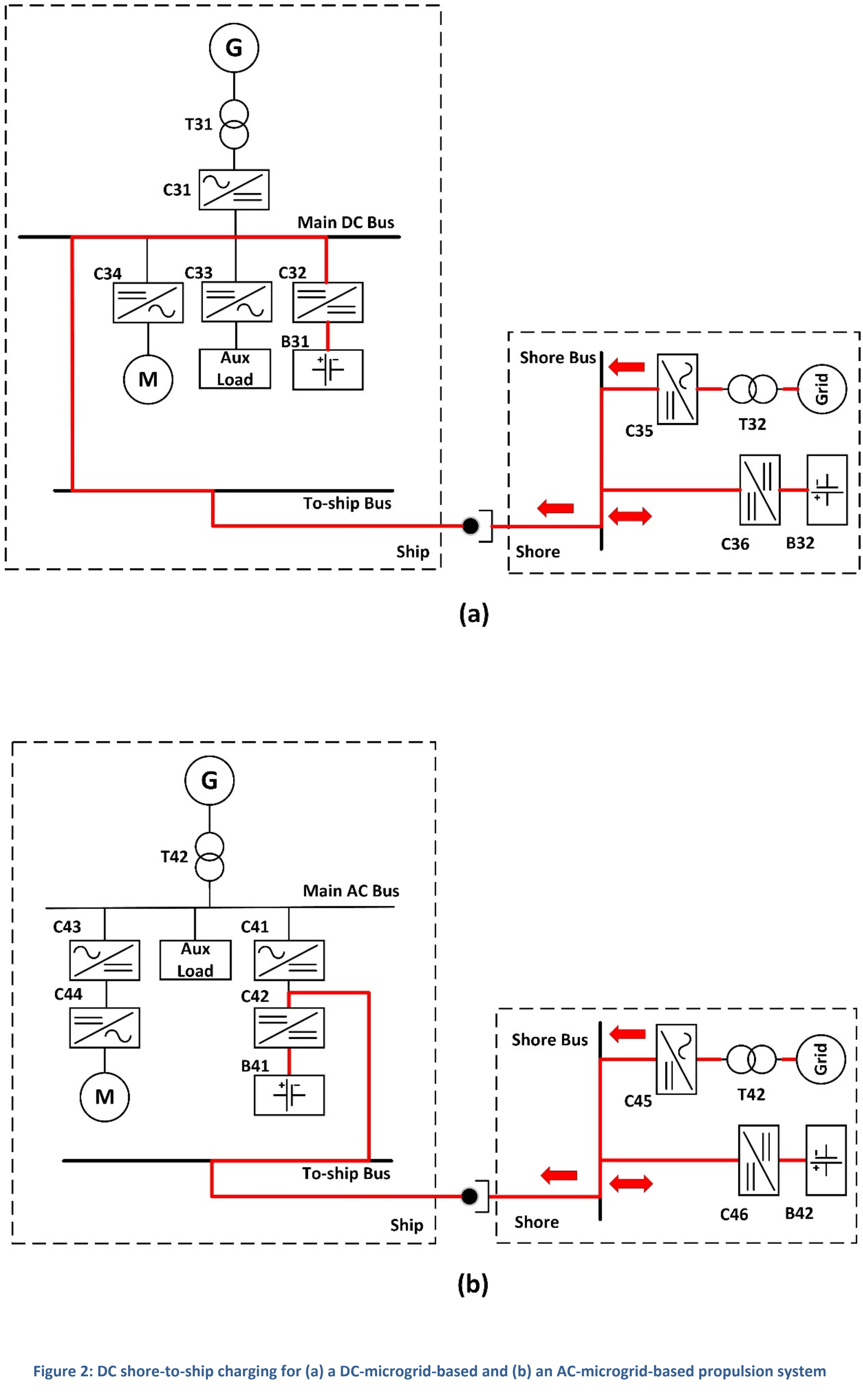


Figure 2: DC shore-to-ship charging for (a) a DC-microgrid-based and (b) an AC-microgrid-based propulsion system

B. 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 is transfer is based on either an electric field or a magnetic field between two plates or coils as a transmitter and a receiver. However, for high power battery charging in electrified transportation systems, mainly concepts for inductive power transfer have been studied and utilized. In marine application, using wireless power transfer technology for shore to ship charging is also promising. In harsh environments with saline 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. In opportunity charging for 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 showed in figure 3.

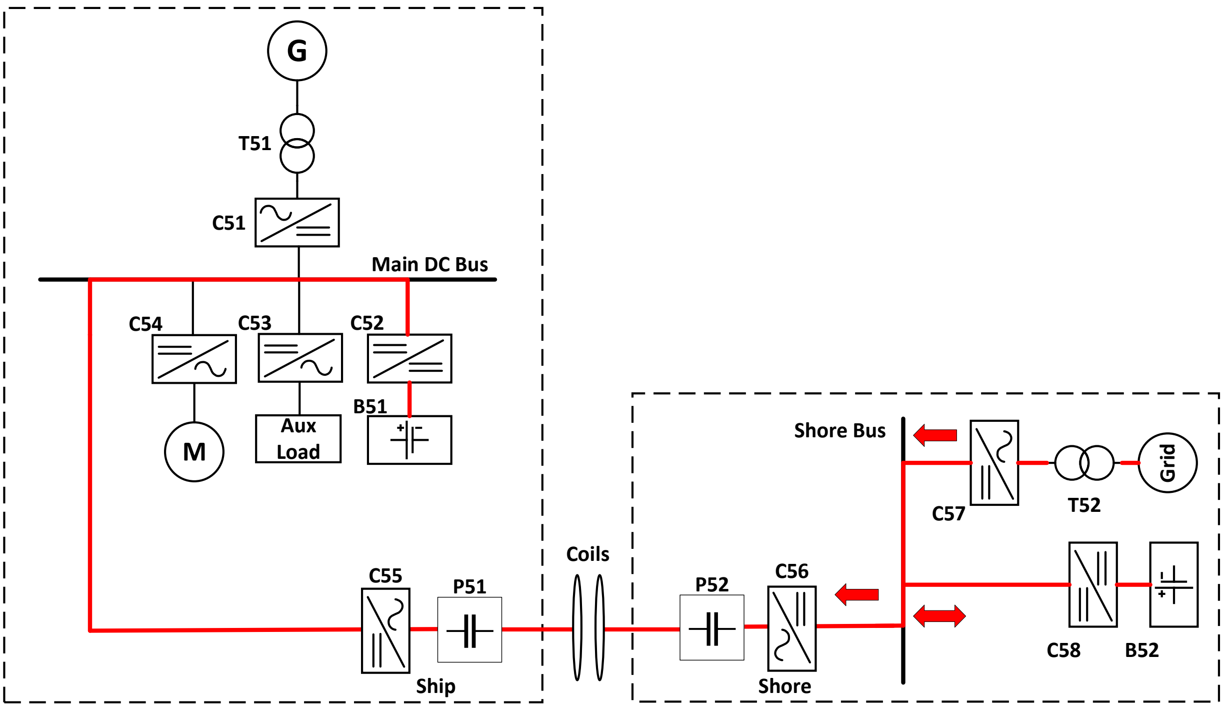


Figure 3: Inductive shore-to-ship charging for a DC-microgrid-based propulsion system

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) are used for generating the reactive power consumed by the coils. Converter C56 generates a high frequency (several kHz) 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 as conventional AC/DC or DC/DC conversion can be utilized, although the control strategy is different from the other topologies. As it can be seen, transmitter and receiver coils provide galvanic isolation, obviating the need for a dedicated onboard transformer. All in all, inductive charging system offers unparallel 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 the cost of the infrastructure. Although inductive charging offers unique benefits, it poses a few challenges. The first challenge is transfer efficiency being sensitive to the misalignment and transmission distance. Increasing the transmission frequency and coil dimensions can improve the efficiency of the power transfer for the same power density, but the limitations of thermal management and power loss exist.

C. Battery swapping method

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 power grid, the battery swapping solution can reduce adverse impacts of charging stations on local power grid, since onshore battery packs are not being charged in a short time, rather they can be charged at off-peak with a cheap electricity or transferred to a central station which may incorporate renewable energy resources, namely wind and hydropower energies. In other words, by using such method a peak load caused by charging for a short time can be distributed into a 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, or otherwise it would be necessary with multiple units.

Although battery exchange technology offers several privileges, it may require large robotic equipment to perform the exchange process and extra battery packs onshore, e.g. large cranes for moving battery packs. Hence, the excessive Capital Expenditures (CAPEX) 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 for local power grid. In figure 4, power system of a battery swapping method is depicted. When the vessel is docked, B51, a discharged battery pack, would get substituted by B52, a fully charged battery pack.

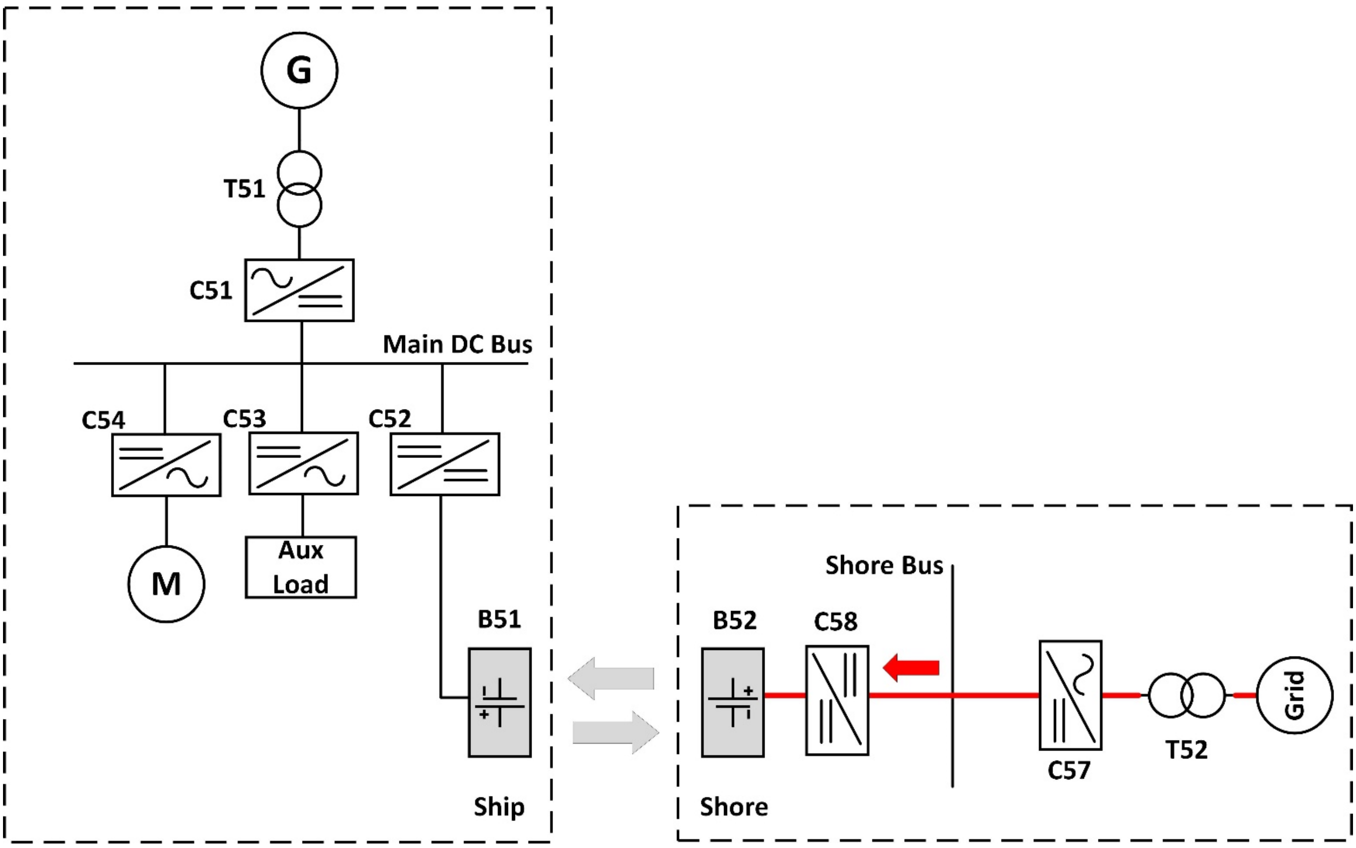


Figure 4: Battery swapping method

III. SHORE-TO-SHIP INTERFACE

Shore-to-ship interface consists of plugs and receptacles, cable management systems, mechanical structures as well as monitoring systems. By looking at previous shore to ship connection projects for cold ironing, most of the connection procedures have been undertaken by assistance of personnel, so carrying several heavy cables, connecting and disconnecting plugs into receptacles. This process is usually taking several minutes and may depends on manual actions. As it can be seen in figure 5, the connection of two cables, each of which is conveying 1.2MW charging power, is done manually. However, for ferries with short stay at berth, automatic connection systems will not only improve the safety of the system, but can also maximize the time available for charging within 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, even though the connection and disconnection times are a small portion of the docking time, it is also recommended to utilize automatic plug systems thanks to their higher safety, flexible mechanism and capability to carry heavy high voltage cables.

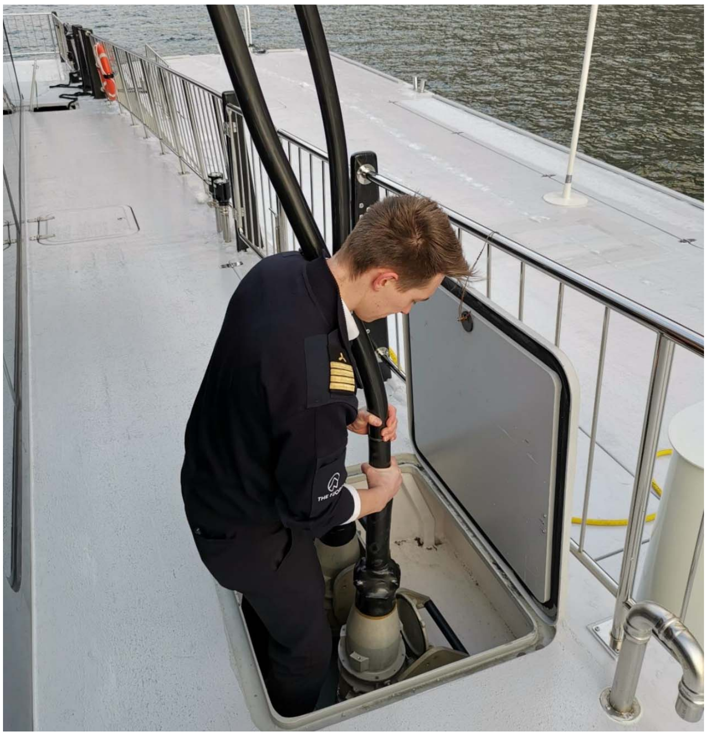
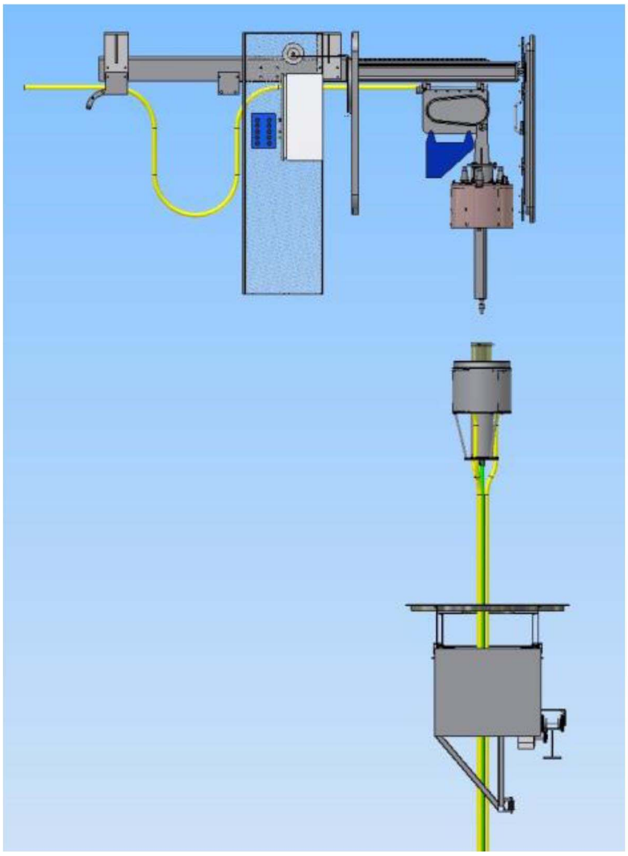


Figure 5: manual connection of two cables for charging the future of the fjords. Photo: Severin Synnevåg

NG3 PLUG is an automated shore to ship connector which has been used for cold ironing and charging purposes. In a typical PLUG system, as it is shown in the figure 6, when the ship is docked a shuttle bar connected to a chain from the ship side above the quay would be lowered down to reach the shore side connector. Next, the shuttle bar gets locked to the quay side connector.

Then, the chain would lift the power socket up to the ship side socket. NG3 PLUG was used for providing Color Hybrid a 2.5 MW night charging and a 6.5 MW afternoon stop charging.



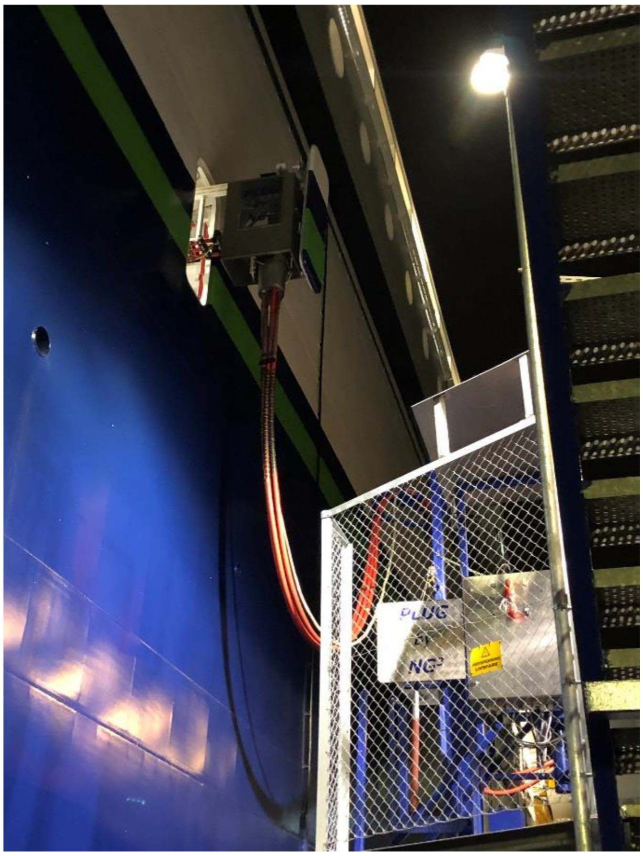


Figure 6: the typical PLUG structure and NG3 PLUG used for charging the Color Hybrid, respectively from right to left, photo: PLUG

For the two sister ferries MF Aurora and MF Tycho Brahe, ABB IRB7600, an autonomous robotic arm, shown in figure 7, is employed for automatically connecting cables through a plug into the onboard charging port. It is placed on land and starts by turning on the robot to be ready for the operation when the ferry approaches the port. It features a 3D laser positioning for recognizing the onboard receptacles in harsh conditions.

Figure 7: ABB IRB7600, an autonomous robotic arm used for charging MF Aurora and MF Tycho Brahe. Photo: ABB

Another plug solution, which has been used for charging MF Ampere and MF Elektra, is Cavotec's Automated Plug System (APS) tower. As it is 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, charging process can start 1 minute after ship docks. In order to make the ferry still and secure at berth, a vacuum mooring system is employed.

Figure 8: Cavotec APS tower used for charging MF Elektra. Photo: Cavotec

Lately, Cavotec has developed another automatic plug-in system called APS Counterweight which is currently in installation in Oslo, Norway. As it is shown in figure 9, this tower is applicable for ferries with charging point in the bow, aiming to reduce the size of onboard and onshore system.

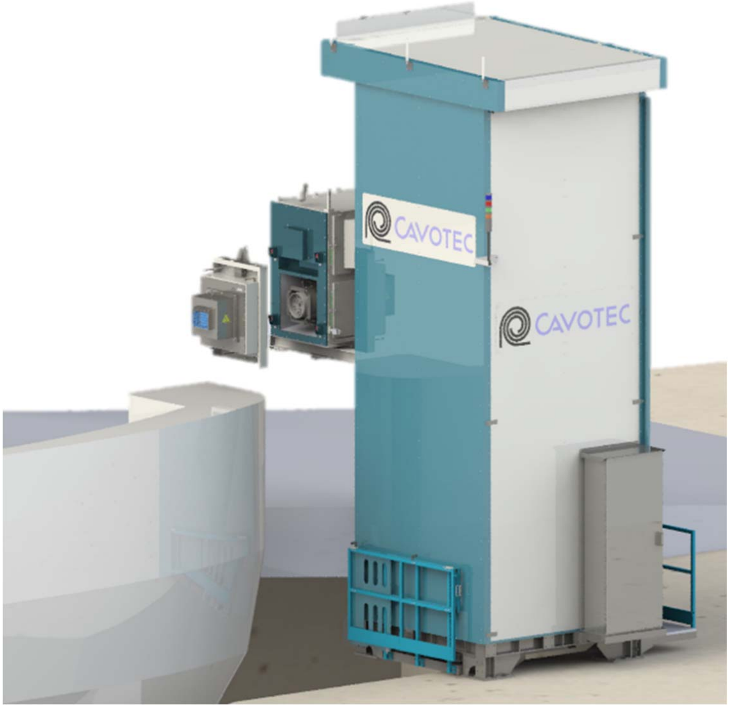


Figure 9: APS Counterweight allows automatic connection with charging point on ferry bow. Photo: Cavotec

Mobimar Nectors™ also provide automated charging connectors for DC and AC systems which utilize the bow section for shore to ship connection using the existing car ramp in order to hinder the effect of ship movements caused by sea level changes into shore charging. This system has been used for the E-ferry Ellen as a 4 MW DC charging connection as is shown in figure 10.

Figure 10: The Mobimar Nectors™ DC-based charging station for E-ferry Ellen, photo: Mobimar

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 feet vertically, within the tower, and 1.3 feet horizontally. The connection process will take less than 10 seconds before charging starts. For Ampere, there are two connection provided, the pantograph-based FerryCHARGER and a Cavotec APS tower similar to the system in Fig. 7. The pantograph system is preferred because it is faster to connect and allows for more motion of the ferry when docked. On the plug system the operator must wait for the arm to extend and lower 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.

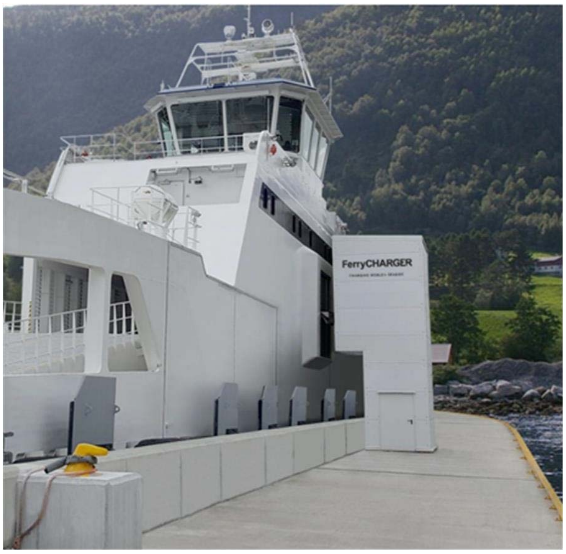


Figure 11: Stemmann-Technik FerryCHARGER. Photo: Stemmann-Tecnik

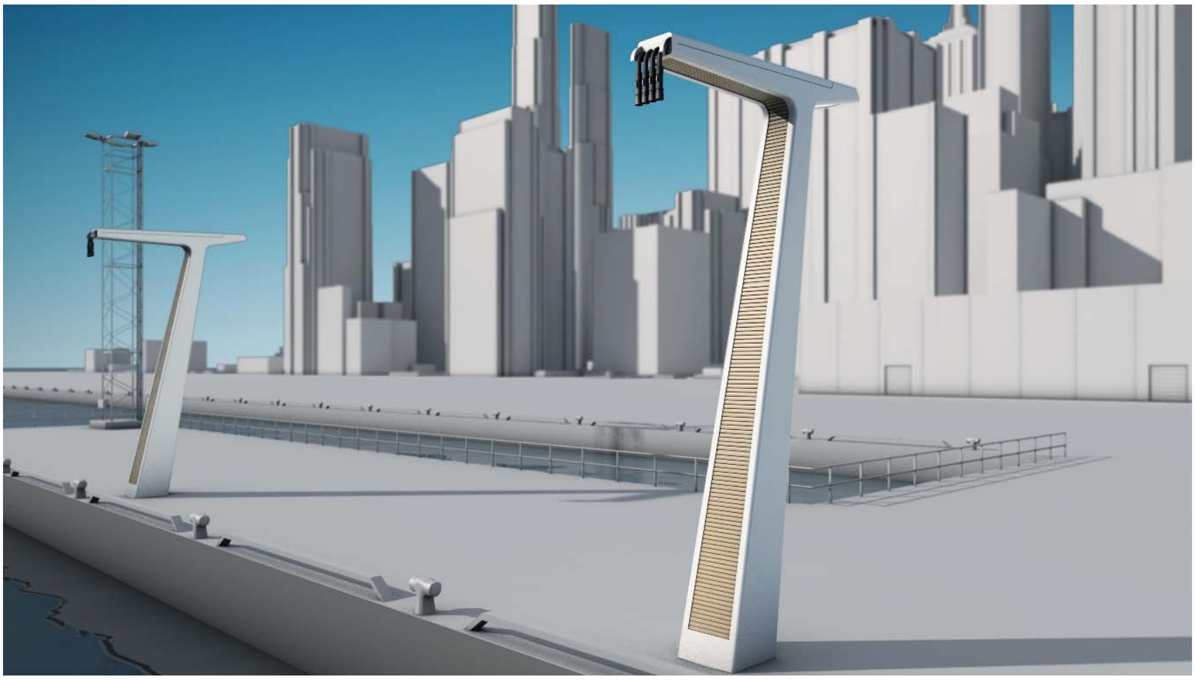


Figure 12: Zinus port power P850. Photo: Zinus Port Power

Zinus ZPP850, as it is shown in Figure 12, offers an automatic shore to ship connection with capable current of 4500 A. It has a telescopic arm capable of 180 degree revolving and 10 meters tidal difference adjustment which is placed on top of a tower. Such arm which can feed 20 meters cables release the cables into the onboard reception, which automatically pulls in the charging cables in a dry and safe environment.

As mentioned earlier, inductive charging is a promising solution for maritime aplications thanks to its contactless operation. In Wartsila's inductive charging system for MF Folgefonn, as it is depicted in figure 12, a robotic arm was used for carrying the onshore, transmitter, coil and approach it close to the receiving coil on ship. This robotic arm does not necessarily track the accurate position. Rather it is designed to compensate the tidal movements which can cause a difference in water level of several meters in some locations along the Norwegian coast and to move the transmitter coil back into a safe position when it is not in use since there can also be a need for other vessels to dock at the same position. As the direct mechanical connection requiring accurate positioning is eliminated in inductive charging, the process can be started as soon as ferry is approaching the onshore installation. By utilizing wireless communication between ferry and the port, the onshore robot arm gets ready for approaching the receiver coil when the vessel is approaching the dock, and the power transfer can start automatically when the distance is low enough.

Figure 13: Wartsila Inductive charging system for charging MF Folgefonn. Photo: Wartsila

Figure 13 shows an inductive shore to ship charging system provided by IPT Technology for an electric shuttle ferry built by Swede Ship Marine operating in Fredrikstad. It operates 24/7 by only one person using a 100kW automated wireless charging solution. Since this ferry crosses a river, there is no major tidal movements affecting the shore to ship connection, so the transmitter coils are stationary.

Figure 14: Inductive shore to ship charging for Go Vakker Elen shuttle ferry. Photo: Swede Ship Marine

IV. Control and Power Management

There are two levels of control in a charging system such as low level and high-level control: 1) low level control includes the control of power converters, namely power control and voltage control depending on the mode of operation; 2) high level control includes the power management system which 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 the state of charge (SoC) and state of health (SoH), thermal management and cell balance. 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.

A. Power converter control

Considering a DC charging system for a DC-based propulsion system applicable for a scheduled ferry, as the system shown in figure 2 (a), 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 voltage or DC side 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 showed in the figure 14, which includes a synchronization block, which is typically a phase locked loop (PLL), a current controller, usually a Proportional-Integral (PI) controller, pulse width 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 which is connected to the shore bus through a bidirectional DC-DC converter. There are two modes of operation for the converter C36: 1) charging from the grid 2) discharging to the ship. For Li-ion batteries, typically charging process is started with a constant current while the battery voltage rises until the moment that the battery voltage reaches a specified value, then the charging would continue with a constant voltage and descending current. The controller for such 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 is controlling 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.

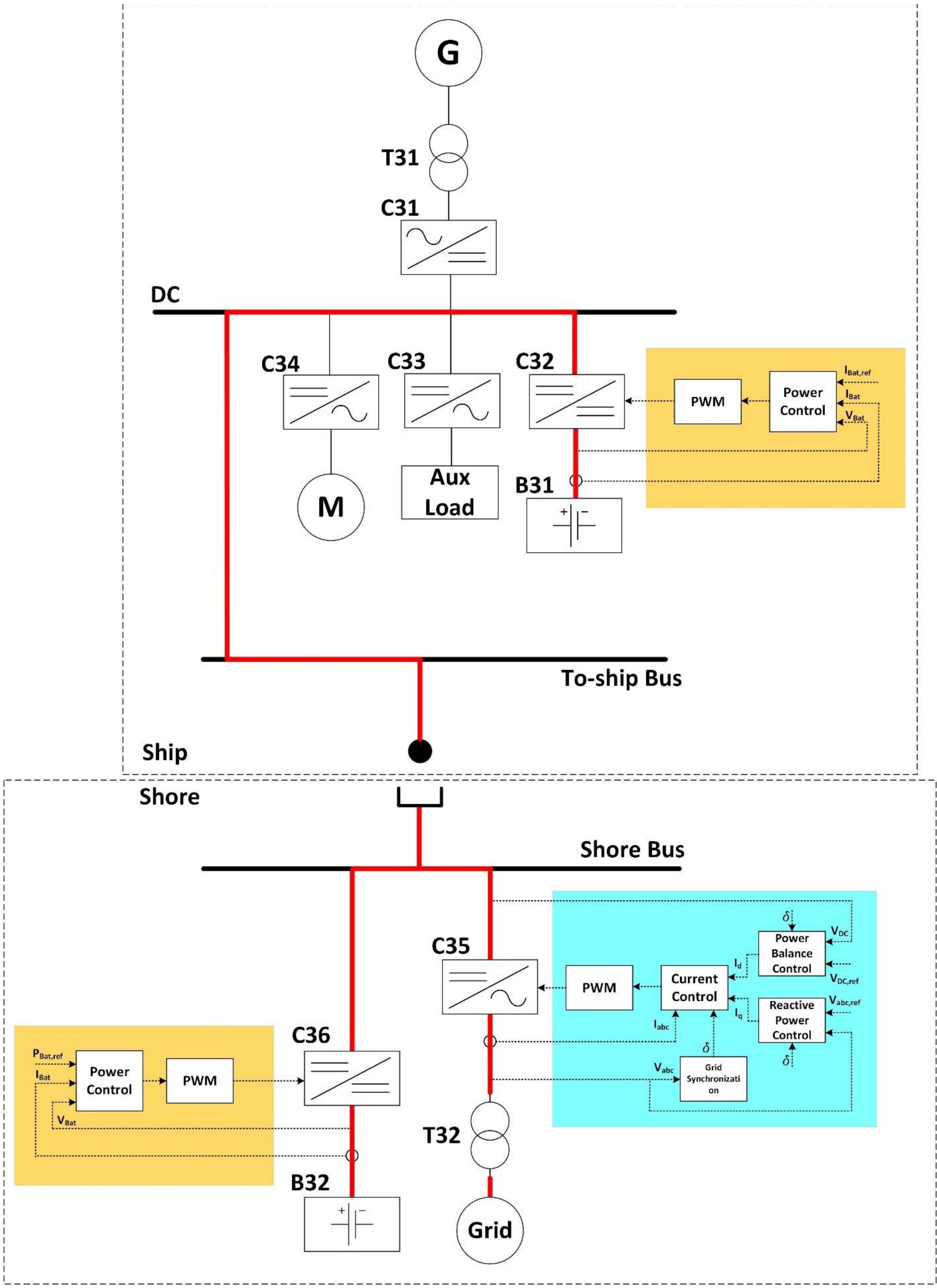


Figure 15. Converter control for charging path

B. System level control

For discussing 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 high-level control scheme is depicted in figure 15. As mentioned in the previous section, at onshore station, onshore battery packs are recharged by the grid and discharged into the onboard batteries, so there are four modes of operation for a charging station: 1) charging onshore batteries when there is no vessel docked, 2) when a vessel is docked and the charging process is 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 the ferry dockings with higher power. Thus, in the charging station, an energy management system (EMS) and a power management system (PMS) are needed for generating the references for the charging power, the charging and discharging power of the onshore battery bank and the power from the grid. Furthermore, a Battery Management System (BMS) is usually used to perform the battery monitoring and battery cell balancing. The BMS communicate with the EMS in order 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 power management system 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 cost by charging during off-peak hours. On the other hand, drawing the charging power from the onshore battery bank has less energy efficiency than using the grid because of the energy loss generated by the additional power electronics converters to interface the onshore battery and the battery itself. In other words, using energy buffers such as onshore battery packs generate additional energy loss in the process of charging and discharging of onshore batteries. Hence, the onshore PMS should choose the optimal share of sources in terms of energy transfer efficiency and power quality issues at 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 10min, and that the ferry will come back at berth for the next charging after 30 min. If the charging power from grid and the onshore battery pack are 200kW and 600kW, respectively, the onshore battery pack can be recharged by the constant 200kW drawn from the gird when the ferry is away. In this case, the drawn power from the grid will be constant.

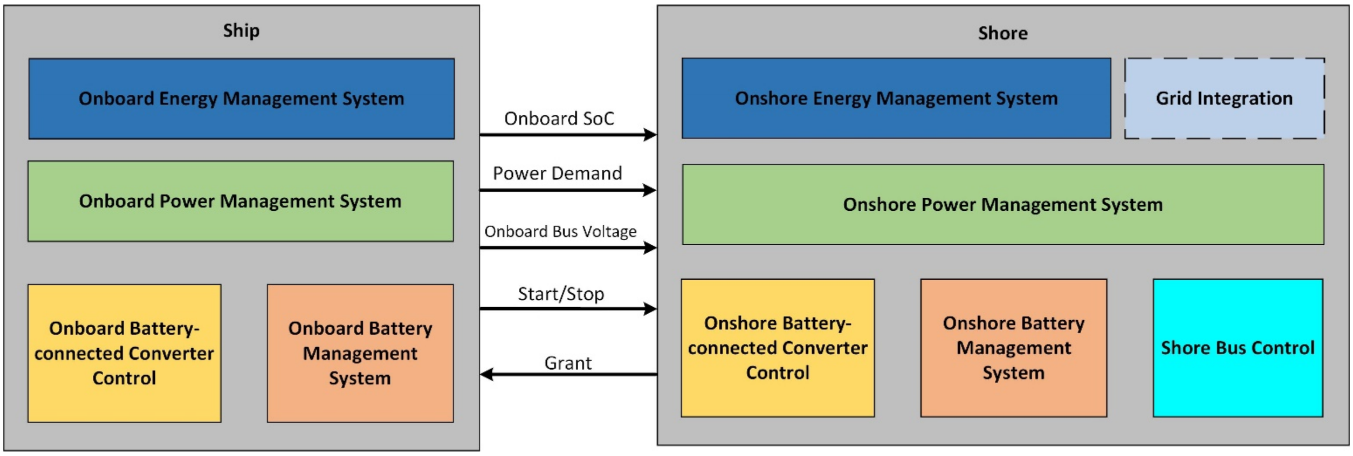


Figure 16. An example of the system-level control structure

For onboard power management system, 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 if the generators are not working. In the second and third modes, converter C32 is only controlling the battery power. Further, during the charging process in which the onboard DC bus is connected to the shore bus, in order to avoid instability, there should not be two converters controlling the DC bus. 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 power management system more complex. During the charging process, monitoring the state of charge and voltage level of the batteries as well as start and stop commands are carried out by means of the onboard power management system.

V. CONCLUSION

In this article, 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 power management has been presented. As 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 land-based grid supported by renewable energy systems for powering the propulsion of marine vessels, although it is challenging to charge the onboard battery within a limited time from a weak grid available in remote areas. In terms of the shore to ship connection for the battery charging, there are two solutions, wired and wireless connections. In the wired solution, there is a plug and receptable or a pantograph to connect the shore power to the ship for charging the 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. Further, in the contactless shore to connection, the electric energy is transferred through the magnetic field by two coils, the transmitter coil onshore and the receiver coil onboard. In this regard, a list of available shore to ship interfaces have been described in this article. The control strategies used for 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 the current and future trends regarding the shore to ship charging and the specification of the ship, a proper choice of power system architecture for the charging system and control strategy plays an important role for improving the efficiency and cost of the system.

VI. FURTHER READINGS

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