The development of a guideline on the selection of a charging and mooring mechanism for electric vessels.

A case study for BC Ferries.

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by

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Master thesis
Mechanical Engineering, Transport Engineering and Logistics
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Preface

This graduation research gave me the opportunity to extend my knowledge in multiple ways, for which I am really grateful. I got the change to dive into the world of maritime engineering which was relative new to me, but I also got the experience of working for such a large company. I am glad that this chance was given to me and it definitely made me more conscious about what I would like to do after I graduate.

I would like to thank all my colleagues within Damen for providing me all new knowledge on vessel designs, electric systems, seakeeping calculations and lots of other insights. But also just for the nice atmosphere within Damen which made the my graduation internship much more fun. Of course special thanks to Erik-Jan. You gave me the space to do the research my own way, but always open for question whenever needed. During our meetings you had always good feedback to push research further in the right direction, which helped me a lot!

Furthermore I want to thank Xiaoli and Henk for supporting me during this research. I did not do a typical scientific study for my graduation research, which was sometimes difficult for both parties. However, you always gave me useful feedback during our meetings that I could use to deliver this finally version of my master thesis.

L. Braam
Delft, 2019

Abstract

Due to the global climate change there is a increasing demand for transportation on renewable fuels. An increasing trend in electric propulsion can already be seen in the automotive industry and this is now also gaining popularity in the maritime sector. Due to limited capacity if the onboard battery, especially electric ferries are becoming more popular, because of the relative short sailing distances. The first electric ferry became operational in 2015 in Norway and since than a hand full of electric vessels was developed. An electric vessel requires a charging mechanism to charge while unloading and loading passengers in the port. Besides, generally also a mooring mechanism is necessary. This enables the vessel to turn off the propeller while charging which limits the energy demand while charging. Various systems have been developed already. However, these are not standardized solutions but all one of a kind systems designed for a specific vessel or fleet. Which of these is the best solution is not easy to determine and strongly depends on the vessel characteristics and the operating environment. To supply the expected increasing demand for electric vessels, a guideline is developed which will help the engineer to find a suitable charging and mooring mechanism and to decrease the selection time for this system. The will provide Damen a strategic advantage towards other shipyards in vessel tenders since both the development costs and delivery time is lower.

This guideline is developed based on the knowledge gained during a case study for a 81m Ropax ferry, sailing in the surroundings of Vancouver Island. For the case study an engineering design method was selected from literature and applied to this case, for which Damen had a hard time finding a charging and mooring mechanism. First thought was to combine both into one mechanism, but this is difficult due to conflicting functionalities of both systems. Due to the limited time available for the research, the design of the mooring mechanism is not taken into account for the case study. Setting the requirements for the charging mechanism is complex due to the range of different fields of interest that should be taken into account. However, the requirements of these various aspects are often related in some way to one another. This makes it easy to lose sight of the structure of all requirements. Comparing the functions that the charging mechanism should fulfill within these requirements and the existing charging mechanisms, it can be concluded that no suitable system is available yet. The gap between these is defined as a set of three functions; to compensate the tidal difference, deal with misalignments between the vessel and the shore and to provide flexibility for vessel motions. A new design was made which covers this gap. Additional research was done to ensure sufficient flexibility from the power cable, since this proved to be critical in the state of the art systems.

From the knowledge gained during this case study, the guideline is developed. The guideline provides insight in the influential factors while selecting an mechanism. This should offer the engineer a structure to set the requirements and ensures that no aspect is left out of the requirements. An overview with the already existing mechanisms is provided which should be consulted multiple times during the process, to check whether a suitable systems exist, if the requirements should are too tight or if the project is not profitable at all. The structure of the requirements is designed such, that the relative easy requirements are set first. This prevents from doing demanding calculations or going on expensive business trips, while it could have been seen earlier that a project is not feasible or profitable at least. The guideline is validated while selecting a charging mechanism for an electric tug. This validation proved to decrease the selection time for a charging mechanism significantly compared to previous projects within Damen. After the test, a charging system was found which is preferred for the tug. This charger is now further discussed with the supplier of the system.

List of Figures

List of Tables

Nomenclature

AC	Alternating Current
BaCO	Battery Charging Options project
COG	Center of Gravity
CSA	Cross Sectional Area
DC	Direct Current
FBS	Functional Breakdown System
GHG	Greenhouse Gases
HV	High Voltage
LV	Low Voltage
RAO	Response Amplitude Operator

Contents

1
Introduction

This graduation research is executed during an internship at Damen Shipyards Gorinchem. First a small introduction of Damen as a company is given in 1.1. In 1.2 the relevance of this research will be described. The objective of this research is settled in 1.3. Afterwards the the approach for this research is discussed in section 1.4.

1.1. Damen

Damen is a family owned company established in 1927 by Jan and Rien Damen in Hardinxveld. In 1969 Kommer Damen bought the company from his father. He came with the the concept of standardization of ships. Ships were built in advance which lead to fast delivery times when ordered by a customer. That standardization of ships also lead to reduced costs and proven designs. This concept is currently know as the Damen Standard. In 1973 Damen expanded to Gorinchem where the headquarter is still located. Besides, there are nowadays Damen yards and business cooperations located all over the world. Many vessels are developed by Damen. Tugs have been an important part of the Damen fleet for a long time but currently the market for other vessels is growing rapidly such as high speed crafts, off shore vessels or ferries.

The design part of this project concentrates mainly on ferries. Although the standardization of ships is an important distinguishing mark of Damen, this does not go for ferries. In order the win the tender of ferry operators, each ferry has to be specially designed for the desired conditions. With the current trend of switching the renewable fuels, the specific design becomes even more important.

1.2. Problem relevance

It is generally known that the exhaust of greenhouse gases (GHG) has increased enormously within the last centuries and so the climate is changing. To prevent further progress of the global warming, the exhaust of carbon dioxide (CO_2) and other GHGs should be reduced. Currently lots of environmental friendly methods are developed to generate electricity without burning any fuel such as windmills, solar panels or hydro power. The energy generated can directly be used for domestic energy supply, but also to charge the batteries of vehicles. Doing so, the combustion engine can be removed from the vehicle and be replaced by an electric motor. This technology is becoming increasingly popular for cars. The amount of plug-in hybrid and fully electric passenger cars in the Netherlands has increased in the last eight years from zero to over 125,000 [8]. However, the use of electric motors for the propulsion of ships is not common yet. The lack of this development can be ascribed to the infrastructure lock-in of current investments, the limited finance for R&D, the risk adversity of investors and the large variety in classes and scales of ships [18]. However the shipping industry contributed in 2007 for 3.3% to the global CO_2 exhaust and is expected to increase only further due to the continuing growth of international seaborne trade [62]. Therefore it is of major importance that the development of environmental friendly propulsion for ships is increased.

Alternative energy resources

Currently the majority of the ships in the world are running on Heavy Fuel Oil (HFO) or diesel. However, since the last decade the attention for alternative fuels has increased in order to decrease the world wide exhaust of GHG. Examples of these alternative fuels are LNG, hydrogen, biodiesel, nuclear power and electric sailing. LNG and biodiesel are generally not considered as long term alternative fuels, since the exhaust of GHGs for these fuels is decreased but not excluded. Therefore, these are rather judged as a transition fuels towards a world with zero GHG emission [15], [61], [43]. Nuclear propulsion is a relatively clean technology when it comes to the exhaust of GHG. However, because of safety and financial reason this technology is in currently only used specialized vessels such as ice breakers and Navy vessels. Also the ports which are certified to dock nuclear powered vessel are limited. For these reasons nuclear power does not seem a reasonable replacement for diesel of HFO propulsion. [30], [74]. A promising alternative fuel which is currently investigated extensively, is hydrogen [52]. However, the required systems to operate on this fuel are not developed yet and therefore electric propulsion is currently an increasing popular way of sailing environment friendly. This is realized by installing onboard battery packs, that are charged while the vessel is docked. This method can realize zero emission propulsion, when energy is generated by sustainable methods such as wind, solar or hydro power [22]. Therefore the technology is seen as the most future proof system and not only a transition solution. Moreover, electric motors create far less noise and vibrations compared to combustion engines. Using electric propulsion would therefore result in a more quite and comfortable ride for the passengers and less nuisance for the surroundings. The major issue with the technology is the limited amount of energy that can be stored in battery packs. However, the development of better batteries is going quickly which enables vessels that travel relative short distances already nowadays to sail fully electric. Since the maximum battery capacity is still in creasing due to new technologies, it seams reasonable to expect that these maximum sailing distance will increase within the near future [83]. Therefore this research is focusing on the development of full electric shipping.

Full electric vessels

The idea of full electric vessel has come in thought at multiple companies. However, it still seems a difficult task to develop a fully electric vessel which performs as desired. Especially to establish a reliable charging connection while the vessel is docked, appears to be hard. An example where charging difficulties are experienced is the EU funded project 'Sail with the current', sailing between Denmark and Sweden. The first year of operation the vessels where still sailing in hybrid mode because the connection between the plug and socket seemed hard the establish and to keep stable when connected [40], [1]. This project and other electric vessels with their issues will be discussed in chapter 2.

Damen has recently sold two ferries to British Columbia Ferries (BC Ferries), located in Canada in the area of Vancouver. These will first be running in hybrid mode, but are already designed to be retrofitted into a fully electric vessel. An impression of the ferry is shown on the cover of this report. Damen has executed a project called Battery Charging Options (BaCO), in which the current existing charging mechanisms are investigated whether these would be suitable for the BC Ferries. However it turned out that no existing mechanism is fitting the requirements for various reasons. These have to do with among others the port layout, the environmental conditions and the required charging power [27]. The exact gap between the requirements and the existing products will be discussed in section 3.5

1.3. Research objective

This research was initially set up to design a charging mechanism that can be used to charge the vessels for BC Ferries. In previous studies it turned out that also a mooring system is required and there for this should be designed in this research as well [27]. Currently the ferries from BC Ferries do not moor during unloading and loading. During this process the ferry propeller is pushing the ferry towards the ramp. Metal structures called wind walls are installed next to the ramp to keep in ferry in place while pushing, as shown in figure 1.1. However, it is preferred to stop the propeller during the unloading and loading. This would decrease the required shore power and minimizes the size of the charging station. So, a mooring mechanism is required to improve the charging efficiency. However, considering the trend seen before for electric road vehicles and the amount of projects announced lately it is reasonable to believe that the demand of full electric ships will increase within the near future [37], [38], [10]. Therefore the goal of this research is: *to develop a generic design guideline for selecting a charging and mooring mechanism for electric vessels.* This would provide Damen the opportunity to quickly develop electric vessel with the supporting shore equipment once this is ordered by a customer. To set up this guideline, the BC Ferries case will be worked out. This can will be used to determine

all influential parameters when selecting and designing these mechanisms. Therefore the sub-goal of this research is to design a charging and mooring mechanism for the BC Ferries case.
The guideline will include ferries but not exclusively. Ferries offer great potential for electric shipping since the sailing distances are relatively short and the docking places are always the same. Moreover ferries do often sail in Emission Controlled Area's (ECA), which are coastal areas with emission limitations. Therefore the need to switch to renewable energy resources is higher for vessels sailing in these areas [25]. However also other vessels have great potential for electric propulsion, for example river cruises, crew supply vessels or the electric tug boat which will be discussed in chapter 4.

Figure 1.1: The ramp in Alert Bay, operated by BC Ferries.

The research will mainly focus on the mechanical properties of the charging and mooring mechanism. However, maritime and electrical aspects should be taken into account to deliver reliable results. This makes the research a multiply disciplinary project. The scope of the research is illustrated in figure 1.2 below. During the research, the port- and vessel design and the required electronic infrastructure are assumed to be present. The scope of the research is to design a mechanism to connect the power supply to the socket. Equally for the mooring mechanism, the goal is to design a mechanism to secure the ship in existing port. Hereby the existing port layout and the vessel design should be taken into account. Also the required electricity transfer should be kept in mind, since this can be crucial for the mechanical aspects of the system. Furthermore the environmental conditions are an important factor to note. This will contributed to multiple varying loads on the structure.

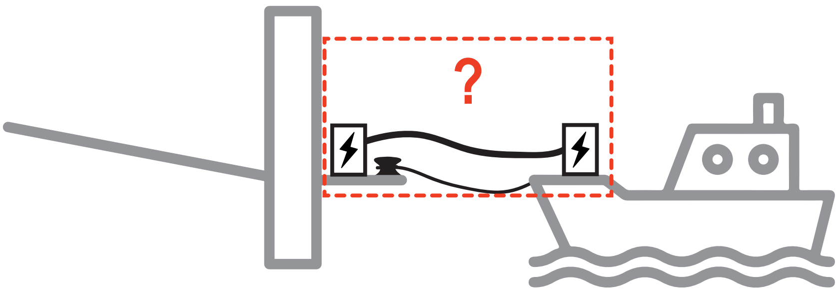


Figure 1.2: An graphical view of the research scope.

1.4. Research approach

To develop the generic guideline for selecting a charging and mooring mechanism for electric vessels, first a general design method is chosen from literature. On the basis of this method a charging and mooring mechanism for the BC Ferries case should be designed. During and after this design process, this method will be adjusted and specified for the development and selection of charging and mooring mechanisms for electric vessels to ease this process for future projects. The chosen general method is the systematic approach described in Engineering Design Methods by Nigel Cross [24]. This method is chosen because it is clearly written for engineering purposes. The working mechanism of the product is the main focus of the method and subjects as the appearance of the product is only a minor subject. In other methods found [41], the attractiveness of the product plays a more important role. Others again, include more product testing in the method than feasible during this research [77]. A schematic overview of this method is given in figure 1.3. The method consists of seven steps that follow up.

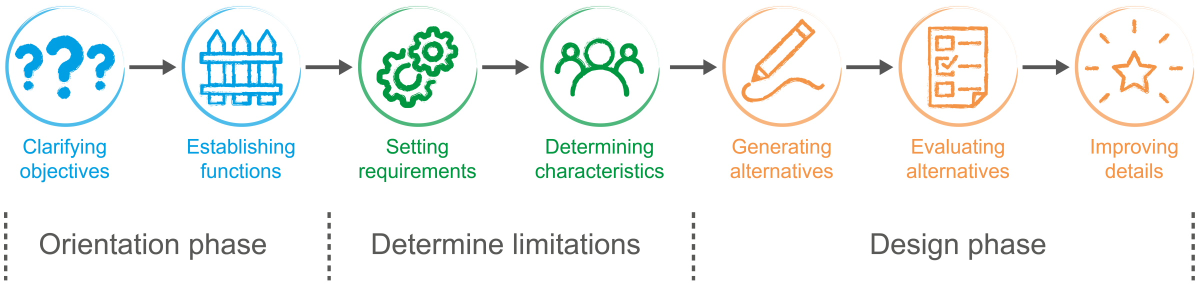


Figure 1.3: The design method that will be applied on the BC Ferries case adopted form [24].

The seven steps can be described as follows.

1. *Clarifying objectives.* Determine the main objective that the design should fulfill. Furthermore, determine also the sub objectives that are enclosed in satisfying the main objective. Order the objectives in a hierarchical order in an objectives tree.

2. *Establishing functions.* Establish the functions that the design should fulfill. Use the black box procedure with a known input and output. The functions of the design should be able to transform the input to the desired output. This will again include the main function and sub functions.

3. *Setting requirements.* Set the requirements that the design should be able to satisfy. This contains only checkable requirements. For example 'the design should be big enough' is an incorrect requirement. This should be formulated as something that can be checked by a simple yes or no. For instance, the design should be at least 3m high.

4. *Determining characteristics.* The characteristics of the mechanism are aspects that can satisfied in a higher or lower degrees. Unlike the requirements these do not have to be specified but can include statements as 'to be as good as possible'. The value of these characteristic is generally not equally divided, but some have a higher priority over others.

5. *Generating alternatives.* On the basis of the sub functions determined before, a morphological scheme is set up. In this scheme, multiple solutions are designed for each sub function. Afterwards sub solutions will be combined again the create multiple concepts. The amount of concepts can off course grow rapidly when the amount of sub functions and sub solutions increases. The goal is to keep the amount of concepts limited by crossing out the unfeasible combinations of sub solutions and by quickly rejecting the least promising designs.

6. *Evaluating alternatives.* The concepts designs remaining will be evaluated into more detail. First of all it is important the check if the concepts fulfill the requirements. If not, one should determine if the concept is inappropriate or if these requirements should perhaps be adjusted. Afterwards one should use the weighted objectives methods to evaluate to which extend the objectives and characteristics are satisfied. This will result in a concept with the highest score which will be the final design.

7. *Improving details.* Once the final design has been chosen, each part is looked over once more. Improvements can be realized in two ways: either by increasing the value of the part, or by reducing the costs of it.

The design method has been divided into three phases. The orientation phase consists of the first two steps where more insight is gained into the actual goal of the design. The second phase covers step three and four, in which the limitations are determined for a suitable design. The last phase is the design phase in which actual new concepts will be designed and thought through. These phases are shown once more in the the research flow chart in figure 1.4. The project starts with the background information, where primary insight will be gained into the BaCO research executed by Damen. Following, the state-of-the-art research will be executed to gain in depth knowledge in currently existing technologies and mechanisms developed for both charging and mooring. After this expertise is gained in the subject, the process of the design method will take of, which will start with the orientation phase to gain additional insight in the objectives from BC Ferries. In the phase following it will be determined which requirements a suitable system should satisfy and if there might be additional preferences on the system from BC Ferries or Damen. After this phase the functions and requirements for the BC Ferries and the commercially available mechanisms will be compared the define the gap between the existing products and the case study. This gap is used to design a new, suitable system for this case. The guideline will be written parallel to the case study. There is chosen to do so, since the case study is expected to be a time demanding procedure and this way, the knowledge of the case study can be used for the guideline when it is still fresh. Once the guideline is completed, it is validated by applying it to a second case, involving a different type of vessel.

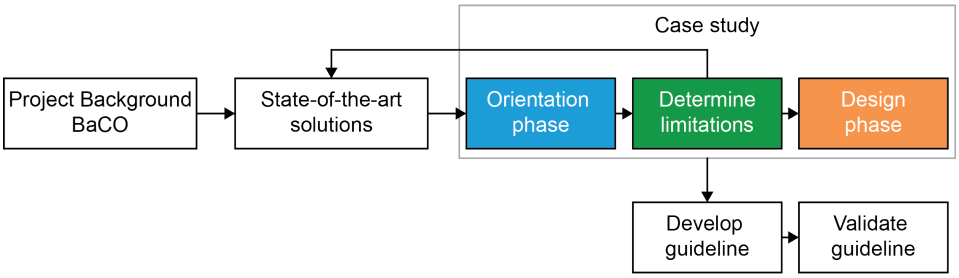


Figure 1.4: The flow chart of the entire research, including the three phases form the design method.

In chapter 2 the current existing technologies for both charging and mooring mechanisms are investigated. This will help to gain insight into the topic and the get a clearer view later, about why there are no suitable systems for the BC Ferries according the the BaCO project. In chapter 3 the case study for BC Ferries will be executed, using the method from figure 1.3. Based on the experiences the guideline for finding a charging and mooring mechanism for electric vessels will be constructed in chapter 4. This constructed guideline will be validated for a different project. The conclusion of this research and recommendations for future research are provided in chapter 5.

2

State-of-the-art solutions

To gain insight more insight in the research topic, This chapter looks into the currently available technologies in this field. In section 2.1 a literature research is executed to see which technologies are able to transfer electric energy, and such, can charge a battery. Afterwords in section 2.2 a study is performed to see which mechanisms are currently available for the charging and mooring of electric vessels.

2.1. Literature on charging technologies

In this section, five technologies are discussed that can be used to transfer electric energy to the vessel battery. These are described in subsection 2.1.1 till 2.1.5. In subsection 2.1.6 a conclusion is drawn on which technologies seem feasible to charge electric vessels.

2.1.1. Conductive charging

The most common way of transferring electric energy is by electric conduction. For this, metal-to-metal contact is required between the shore grid and the ship battery in order the let energy flow. Conductive charging is the most ordinary way for charging batteries such as for mobile phones, laptops and also electric vehicles (EV) are generally charged by conductive charging. Three power levels have been determined for the EV charging. The lowest level is easy to implement on the domestic electricity grid, but it comes with a long charging time. Higher power levels are more demanding to install, but the charging time is decreased significantly [88]. Since the power demand of electric vessels will be much larger compared to EV's, the power output of the charger should be larger as well in order to achieve a reasonable charging time. This increased power supply will result in higher investment costs. This is due to multiple factors such as the investment to the shore grid to supply enough power, the larger cables and plug required for the demanded power supply, the increased dimensions for the additional electric equipment and the required safety measures. The major advantage of conductive charging is the high efficiency of the energy transfer, which is nearly equal to electricity flow through a power cable. The International Electrotechnical Commission (IEC) has set up an international standard for shore connection systems for both high and low voltage connections. Although the low voltage part is still a pre-standard, these both provide an overview of the impact of conductive charging of vessels [48], [49]. These standards do not contain specific design requirements, but rather safety aspects that should be taken into account that should be taken into account to ensure electric safety. This includes also the safety tests that should be executed in the case of new developed design.

2.1.2. Inductive charging

The previous section has revealed that the physical connection between ship and shore grid can cause issues do to the sensitivity to vessel motions. An alternative way of transferring electric energy is inductive charging, for which no physical connection is required. Although this technology is not as common as conductive charging, it is developing rapidly in this current society which is more and more depending on electric energy. Since inductive charging can start automatically when the device comes near the charger, charging becomes easy and less time consuming compared to conductive charging. Also in the automotive industry, the enthusiasm towards inductive charging is increasing. The working principle of inductive charging is similar to the way transformers work. A current is running through a metal coil or wire, which creates a magnetic field around it. When another coil in placed in the magnetic field, a current through the second coil is induced. This induced electricity can be stored in a battery. The efficiency of the energy transfer depends on among others the coil alignment, the number of turns and the distance between the coils [87]. When charging EVs generally the transmitting coil is embedded in the parking spot, while the receiving coil is mounted underneath the vehicle [34]. Because the air gap is relatively large in this case, the efficiency will only be around 10%. However implementing coupled magnetic resonance can increase the efficiency up to 90%. This basically implies that frequency of the alternating current through the transmitting coil is corresponding with the resonance frequency of both coils [44].

2.1.3. Radio frequency

Another technology for wireless charging that has been researched is radio frequency (RF). Although this technology is not applied on yet on large scale, research has shown that mobile phones can be charged by using RF. The basic architecture of an RF charging system is shown in figure 2.1. Form the small base station (SBS) a radio signal with a certain frequency band and waveform it emitted. The chosen frequency depends among others on the operational environment, the expected attenuation and the RF regulations. The signal can simply be emitted omnidirectional, however the energy received by the device is less. To obtain a stronger power transfer to a specific device, beam forming is required. This radio frequency beam is picked up by the device antenna converts it back to electric energy. The efficiency of this conversion is varying. Research to RF harvesting for mobile phones charging results in efficiency's varying between 4% to 60% [67], [51].

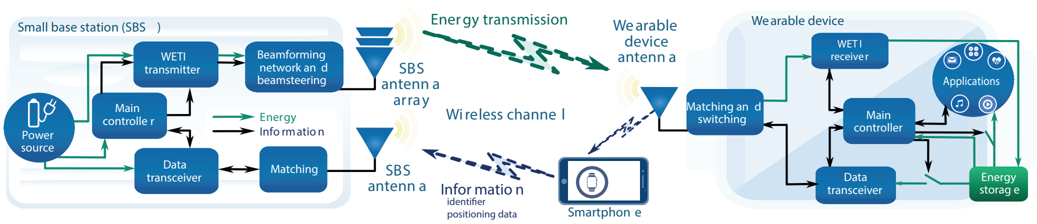


Figure 2.1: The architecture of a RF charging system to charge a mobile phone [35]

The research found until now focuses on charging of mobile phones and other small devices, where the power demand is generally low. The highest power emitted by the SBS in these researches is 20dBm, which corresponds with 100 mW. However if this could be increased to for instance 90 dBm, this would be equal to 1 MW. In theory this should be feasible, however this means that this covers a large great part of the radio spectrum which is used nowadays for all ways of wireless communication. The test in [67] for examples operates at 915 MHz, which is equal to the operating frequency of the radio location devices of the land military systems in the USA and Europe [82], [86]. Emitting a high dBm over this frequency to charge a vessel would cause failure of the radio location system in the adjacent areas. Therefore the maximum radiation power is restricted to 8 dBm or lower for this operating frequency [79]. Since all operating frequencies in the radio spectrum have been assigned to "something", it can be assumed that RF charging will not be a feasible solution for vessel charging, even if another operating frequency was chosen. The level of demanded power will cause issues to another technology in any case in the current society.

2.1.4. Infrared charging

Another wireless charging method developed is infrared charging. The basic idea is that a transmitting unit transmits infrared radiation towards a mobile device. This device is equipped with a radiation sensitive receiver. This convert the infrared radiation back into electric energy which is stored in the battery. Although this might seem like a new way of charging, it is in principle equal to energy storage from sunlight with solar panels. The radiation sensitive receiver is basically just a photovoltaic (PV) cell that can convert light into electric energy [9]. The efficiency of PV cells depends on multiple factors, but in general this is between 6-20% [26]. Since this much lower compared to the other wireless charging methods discussed before, this does not seem like a favorable technology for vessel charging.

2.1.5. Ultrasound

Ultrasound charging is a method developed especially to charge electric medical implants such as pacemakers. Unlike electromagnetism, power transfer by ultrasonic cause no interference with the electric circuit of the device and it is harmless to a living body [55]. The system set up of ultrasonic charging is shown in figure 2.2. Acoustic waves are send from the control unit (CU) to the transponder (TR), which both contain oscillators, over a distance d and frequency f_0. The resonance frequency of the oscillators is typically around 1 MHz for medical implant charging. V_{in} is applied to CU, which generates the mechanical vibrations. TR converts this vibration back into an electric signal, providing the available voltage of the implant circuit V_{av}. Afterwards the voltage is boosted up and rectified to the correct voltage to be stored in the battery [64]. The energy transfer efficiency of the experiments analyzed, is varying between 10-20%. It is important to realize that in these experiments, the ultrasonic waves are transferred through either a water tank [64] or through the skin of a goat [55] which contain a high water percentage. Ultrasound transmission through air will result in a decreased efficiency due to the lower density of the transfer medium. Ultrasound charging mechanisms to charge larger devices such as mobile phones and tablets are currently under development, which are supposed to transfer ultrasound through air [65]. However these are still in concept phase and their expected performance is unknown.

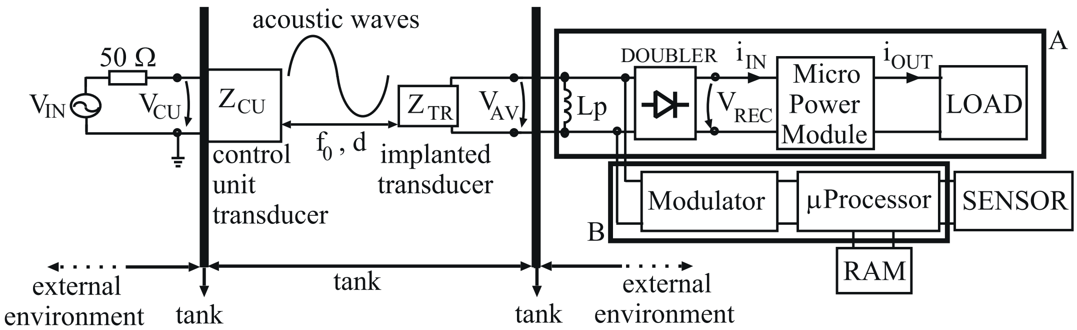


Figure 2.2: The block diagram of a proposed ultrasound charging system [64].

It is unknown if this mechanism could be scaled to provide enough power to charge a vessel battery. In theory this might be feasible, but one could wonder if this is desired since the power demand is high and the efficiency is small with respect to other energy transfer technologies. Since this boat is in the water during charging, energy transfer could possibly be executed in the water underneath the vessel to maximize the efficiency. But even then, the transferred energy should be 5-10 times the demanded energy to charge the vessel which results in expensive operation. Furthermore the cyclic pressure changes might cause damages the the vessel hull.

2.1.6. Conclusion

Various technologies where discussed in this section that can transfer electric energy, and so, possibly charge an battery. However, not all technologies can be used to charge the battery of an electric vessel, which has significantly higher power demand compared to mobile phones or laptops. The first technology rejected is radio frequency. Enabling charging in the order of mega watts, which is demanded for vessel charging, requires a high dBm emission. The level of dBm emitted would block all other radio frequency signals in the surroundings and thereby disable all wireless communication used for mobile phones, radio broadcasting etc. Since the currently society is largely depending on this forms of communication, this is not a desired solution. Also ultrasound does not seem feasible to charge the vessel battery. The ultrasound should be transmitted through the water due to lower losses compared through transmission through air. However to transfer the required power that should be emitted to charge the vessel battery, would cause a large cyclic pressure and the vessel hull. This would damage the vessel hull. Besides the fact that radio frequency and ultrasound are not feasible, their energy transfer efficiency is also significantly lower compared to some other technologies. Equal applies to infrared charging, with a typical efficiency around ..%. Since the power demand for electric vessel charging is already much higher compared to other charging purposes, it is desired to limit the nett power and use a high efficient power transfer method.

For the continuation of this study, only conduction and induction will be considered as a possible technology to charge and electric vessel.

2.2. Available mechanisms

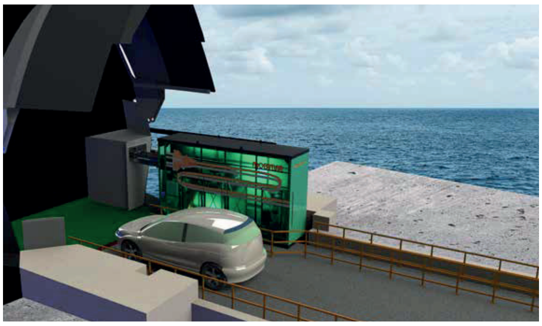
In this section a study will be executed to the mechanisms that are commercially available nowadays. In 2.2.1 the charging mechanisms that are currently available are divided in different categories. Of each category some example systems are provided and their main features and limitations are described. In 2.2.2 this is also done for the existing mooring mechanisms.

2.2.1. Charging solutions

In this part the charging mechanisms that are currently available to charge an electric vessel will be discussed, categorized based on their working principle. For each charger category some examples will be described and the main features and limitations are provided. Notice that the limitations are not necessarily disadvantages, since they might not be relevant for certain cases. Whether the limitations cause an issue depends on the vessel type, the vessel design and the operating environment.

Extendible Arm

Multiple manufacturers have developed a mechanism based on a extendible arm. The working principle of these solutions can be described a as arm extending in only direction. The freedom of movement into other directions and rotations in typically low. One of such a system developed by the is the Finnish shipyard Mobimar, who developed the Nector ™ shown in figure 2.3a. The Nector is currently just one system, but in the future the Nector family should consist of multiple models with varying power levels and DC or AC power supply [58]. The Nector is activated by a push button after which the arm will extend from the housing and automatically find its way into the socket on the vessel. The first Nector has just been installed in the beginning of 2018 for the E-ferry project. This is an EU-funded project obtaining to sailing electric between Ærø and the coast of Denmark. Actual operation of this ferry is planned within the first quarter of 2019 [33]. Therefore the Nector ™ is not a proven concept yet, but is has successfully passed the Factory Acceptance Tests. Another mechanism is the FerryCHARGER from Stemmann-Technik shown in figure 2.3b. The first version of charging tower has been installed in 2015 already to charge the MF Ampere in Norway and since than, several more of these have been installed. The working principle is comparable to the Mobimar Nector. However, the Nector compensates for the tidal difference by being located on the ramp which adjusts moves along with the water level. The FerryCHARGER is positioned on the shore and within the tower, the plug can be moved vertically to compensate for the varying water level. Since multiple FerryCHARGERS have already been installed and are operating for quite some time now. Therefore this mechanism can be considered as a proven concept [57], [80], [27].



(a) The Mobimar Nector™[58]

(b) The Stemmann-technik FerryCHARGER [29]

Figure 2.3: Charging mechanism based on the concept of an extendible arm

Features

- The connection time is relatively short, due to the short distance that should be traveled by the arm. Because connecting and disconnecting is fast, more time available for the actual charging.

- The plug finds its way to the socket automatically, based on the signals from optical sensors. The implies that no human intervention is required to establish the connection. This results in minimal risks for the vessel operator and possibly even decrease the amount of staff required on the vessel.
- Pilot pins in the plug register the proper connection between plug and socket. When disconnection occurs, this will be registered by the pilot pins first after which the plug is retracted form the socket. This way, short circuit can be prevented.

Limitations

- The extendible arm system is a relatively stiff mechanism, which make is hard to ensure a stable connection while the vessel is exposed to water motions and wind. From an extendible arm concept form Cavotec which is observed by Damen, it is know that less than 20% of the connection attempts in successful. However the arm of this concept is relative short compared to the Nector™. The Nector™ has a flexibility in y and z direction of ca. ± 200 mm.
- The Nector ™ has a significant weight, ca 4500 kg, and footprint 5.5m x 1.5m (l x w). The system is design to be placed on the ramp, so the ramp in the case should have sufficient space and strength to support the system.
- The FerryCHARGER is designed to be installed at a fixed next to the ferry in the water. This system comes with a footprint of 3.3m x 4.0m and a weight of 18,000 kg. The tower is supposed to be installed on the shore next to the ferry. There is enough space and sufficient foundation required on shore in order to install the system.
- The automatic connection of the plugs relies on optical sensors. This can make in the system less robust to external disturbances.

Robotic arm

ABB has developed a mechanism which appears to be a more advanced version of the extendible arm concept, since the robot arm can maneuver in six degrees of freedom. Initially this robotic arm mechanism has been developed for the project 'Sail with the current' from HH Ferries. It should charge the electric ferry connecting the coast of Denmark and Sweden. For this purpose the robot arm was designed with the plug on the end of the arm. When the ferry arrives in the port, a shutter opens up which reveals the sockets on board of the vessel. Afterwards, the robot arm can automatically plug-in the plugs in the socket. If the vessel is done charging, the robot arm can retract the plugs again and its moves to its rest position. ABB also designed a robot arm configuration where the plugs are on board of the vessel. In this case, the plug is picked up by the robotic arm and brought to the socket on the shore. The system was installed already in 2017, but the optical sensors of the plug where facing issues to connect automatically due to disturbed signals caused by sunlight. However, since November 2018, the systems is fully operational [6].

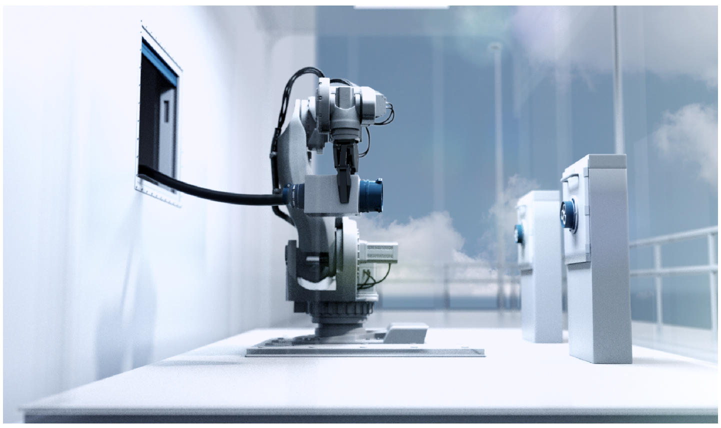


Figure 2.4: The robotic arm charger designed by ABB [4].

Features

- In contrast to the relatively stiff extendible arm concept, the robotic arm can maneuver in six degrees of freedom. One would expected that this increases the stability of the plug-socket connection while the ferry is moving due to the waves and wind acting on it.
- The plug is guided to the socket by optical scanners. Therefore the electric connection can be established without any human intervention. This minimizes the risks for the ferry crew and perhaps decreases the amount of crew required on the ferry.

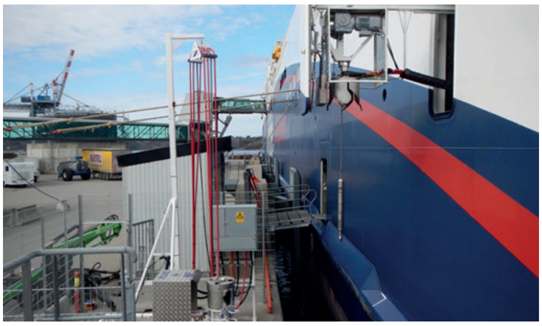
Limitations

- The total system comes with a significant footprint of ca. 2.5m x 2.5m. The weight is expected to be at least 10,000 kg based on its dimensions and incorporate control systems. The mechanism should be located on the shore next to the vessel. The port in the case should have sufficient space and foundation available to support the system.
- The connection between the plug and socket depends on the signals form the optical scanners. This decreases the robustness of the mechanism relative to a mechanism which does not depend on any sensor data. The can also be traced back form the fact that the system has not been working for a year when already installed.

Automated crane

The first automated crane mechanism is the Automated Plug-in System (APS) form Cavotec as shown in figure 2.5a, developed to charge the MF Ampere. The plug of the APS is hanging on the side of the charging tower. When the ferry arrives in the port, the plug extends from the tower and lowers into the socket on the side of the ship. The plug is connected to the tower by three copper charging wires and two steel cables which carry the weight of the plug. After charging, the plug is brought back to its original position to protect it from the weather conditions. Nowadays, a second APS have been installed in Finland to charge the ferry 'Elektra'. Therefore it can be argued that the APS is a proven concept. However the first mechanism came with some operational failures, which will be discussed in the limitations part. If these have been solved in the later version is unknown since the Finnish ferry is hybrid driven and so it is not fully dependent of the battery power supply [75].
Another automated crane mechanism called PLUG is developed by the French NG3, shown in figure 2.5b. This small company has developed a different kind of crane mechanism which lifts the plug from the shore by a small guiding wire and pulls it up into the socket. The guiding wire is connected into the socket by a so called "shuttle bar". This bar automatically finds its way towards to the center of the socket by feedback from three optical cameras. Multiple mechanisms have been installed current, for example in Kristiandsand and Larvik in Norway. Therefore NG3 can be seen as a proven concept, but these installations are only used for shore power and not for charging of batteries [32].

(a) The Automated Plug-in System developed by Cavotec [19]



(b) The NG3 PLUG, Power Generation during Loading and Unloading [32]

Figure 2.5: Automated crane charging systems.

Features

- Since the plug is connected the cable, the flexibility of the mechanism is expected to be higher. This should allow a wider range of vessel motions during charging

- The connection between the plug and socket is established automatically. The plug is guided by optical sensors in the case of PLUG and by laser scanners in the case of the APS. Therefore no human interaction is required to establish the electric connection. This minimizes the risks for the vessel crew en possibly decreases the crew required on board of the vessel.

Limitations

- Although the crane mechanism is supposed to provide extra flexibility, this appears to be less effective as expected. Especially for the APS, the connection is sensitive to vessel motions. The plug is ca. 800 kg to make it drop down automatically into the socket. Due to the large weight, the plug has a large inertia which makes is sensitive to fast motions of the vessel [75].
- The connection time is relatively large compared to other automated solutions, because the distance to travel by the plug is larger than in other solutions. For the APS this is approximately 1 minute, for the NG3 this is even about 2 minutes.
- Both mechanisms have been designed to connect automatically. To do so, sensors are required that let the plug find its way to the socket. The required sensors can make the system less robust and more demanding to maintain.
- In this case of low tide the plug is supposed to drop relatively far to reach the vessel. This may cause the plug to resonate in windy conditions, which increases the risk for damages in the case the heavy plug hits the ferry, a vehicle or even a passenger.

Manual crane

Also manual operated crane chargers have been developed, among others by Cavotec. They have developed the manual crane as shown in figure 2.6a to power the hybrid ferry 'Vision of the Fjords' and the fully electric ferry 'Future of the Fjords'. These are both passenger ferries developed for sightseeing tours in the Norwegian Nærøyfjord. Once the ferry is docked, the crane is remotely controlled by the vessel crew to bring the plug near to the socket. Next, crew should manually plug-in the two plugs and secure them by pulling a handle. When the ferry has been charged, the plugs should again be unplugged manual from the socket after which the crane can be rotated away from the vessel. Other comparable systems have been developed by Cavotec but also by other companies such as ABB and Stemmann-Technik. However, most of these are purposed to provide shore power for the on-board system of larger ships while docked and not for battery charging. One of these is the shore power supply crane from Cavotec installed in Hoek van Holland, to provide shore power to the Stena Line vessels. This system, shown in figure 2.6b was visited during this research to do observations [7], [75].

Features

- As already stated for the automated crane, the advantage of the crane construction is mainly the provide extra flexibility to the plug compared other mechanisms.
- Because the plugs are connected manually to the socket, the connection does not depend on any sensor signals. This make the system relatively more robust.
- The movements of the crane are remote controlled. This minimizes the physical effort required from the vessel crew.

Limitations

- Due to the manual operation, the connection time is in general longer than the automated solutions. This will be in the order of a couple of minutes.
- Because the physical effort required from the operator must be limited, the weight of the cable and plug must be limited as well. According to IEC 80005, the maximum force required to plug in and out it 240 N. For relatively high power demands this means that either the current should be lowered or the multiple plugs should be installed parallel to each other.
- One member of of the ferry crew should be available to assist the charging mechanism. This could possibly lead to an increase of operational costs.

(a) The manual operated crane charger from Cavotec, charging the Vision of the Fjords [78].

(b) The Cavotec crane in Hoek van Holland to provide shore power to the Stena Line vessels.

Figure 2.6: Manual crane charging systems.

- Manual operation increases the possible risks for the operator. Risks that one could think are for example the operator getting hit by the swinging plug, or when the operator is in contact with in plug as a short circuit occurs.
- Extra training of the vessel crew is required to provide the charging. This is especially the case with HV operation, since there are legal safety limitations on working with HV connections.
- As already mentioned before, the tidal variation can create a large gap between the plug and the socket. This implies that the plug is supposed to drop down a relative long distance. This can cause a swinging motion of the plug which creates a danger for the vessel and its crew.

Inductive charging

Wärtsilä has developed a inductive charging system, and installed such a system the to charge the MF Folgefonn in Norway as shown in figure 2.7. When ferry the approaches the port a signal is send by the vessel crew to the port, which is transmitted by a WiFi connection. This results that the charger moves to operation position and is switched on. Once the vessel arrives and the overlap area between both boxes is at least 75%, charging starts automatically, The charging plate is supported by multiple hydraulic cylinders which enables it to move along with the moving ferry. When the ferry sails of, the induction change will be noticed by the charger and will automatically switch of [85], [27].
Features

- The demand for a connection between plug and socket is avoided. This implies that the ferry movements will not cause errors in the electric connection as is often the case for other mechanisms. This is beneficial for the service reliability.
- No human intervention is required to start charging. This minimizes the risks for ferry crew and the passengers. Possibly the required amount of crew on board of the ferry is even reduced.
- The signal of the ferry entering the port is sent by WiFi and this way the need for optical sensors is eliminated. This is valuable to improve the robustness of the mechanism.

Limitations

- The box dimensions are relatively large and heavy with respect to the power that the can transfer. The boxes are ca 2.8m x 0.7m x 1.8m (l x w x h) and weigh 2500 kg. These can transfer 2.5 MW [27].

Figure 2.7: The inductive charger developed by Wärtsilä [85].

- The efficiency of wireless charging is in general less than for the other solutions. The level of efficiency depends in on the alignment of the two surfaces and the distance between these. According to Wärtsilä the maximum efficiency is 97-95% [85], but scientific research shows rather a maximum efficiency of ca. 90 % [87]. In general this is significantly lower than a physical connection. This implies that the electricity costs will be relatively high.
- The investment costs of the wireless charging mechanism is relatively high. The current Wärtsilä inductive charger is available for approximately €1,500,000. This includes one shore installation and required on board equipment.
- The ferry send a signal via a WiFi connection to the charger once it is approaching the port. This means that the mechanism does depend on a internet connection. This might make the system less robust.

Battery replacement

Currently there are no proven technologies available in the shipping industry, but developments are showing that this coming soon. The start-up Skoon Energy has developed replaceable batteries for vessels called Skoon Boxes. These are put in standardized containers, which makes them easy to place in container vessels and to transship them with the standard ship-to-shore cranes. The operation of the first Skoon box is planned in 2019, providing energy to an 110m inland container shipping vessel [17].

Features

- Battery replacement would rule the main issues that occur when using a plug connection. Although the connection between the battery and the shore is still required in order the remove the battery, the stability of this connection is less important. First of all, because the connection is meant to move the battery and therefore is not required to keep still. But more importantly, it concerns in this case a mechanical connection instead of an electric connection. This implies that the connection is not sensitive to any errors in the electric circuit.
- Since the batteries are charged on shore while the vessel is sailing, the available charging time for the batteries is larger. Therefore the peak power requested form the grid is decreased, which decreases the energy costs.
- Less on board equipment is required, such as transformers, rectifiers or pantograph for charging. This saves in vessel weight which decreases the energy consumption of the vessel and safes costs for the development of the vessel.
- The interested thing about the Skoon boxes specifically is, that is using a proven method. Even though the battery replacement is not a proven concept yet, the transshipment of containers is a well established technology.

Limitations

- The dimensions of the Skoon boxes are equal to the dimensions of a 20ft container. This means that there should be sufficient space available on the vessel to install these.
- Since the batteries have to be replaced continuously, they should be installed on a place on the vessel where they are easy to reach. So they cannot be incorporated in the hull for instance.
- Skoon boxes are replaced by standard ship-to-shore crane. To make this possible, the vessel should dock in a port where these cranes are available.

2.2.2. Mooring solutions

In this section the currently available mooring technologies are described. In each category some specific products will be highlighted, the working principle is described and the features and limitations are given. These can be used in the next chapter to investigate whether they are suitable for the BC Ferries case.

Manual solution

Although there have been developed several mechanisms to automate the mooring of vessels, manual mooring is still the most used procedure. Ropes are generally coming from the vessel and are either thrown to the shore, or are brought to the shore by tug boats in the case of larger vessels. These ropes are secured around a capstan located on the quay. Afterwards the ropes are put on tension by either human pulling force or a by a winch on the ship. To release the ship the ropes are slacked again after which the ropes can be manually removed from the the capstan. Semi-automatic mooring solutions have been developed which ease the manual effort require for mooring. One of there is the quick release hook from Trelleborg. This can release the ropes by a simple push on the button. An example of these is shown in figure 2.8a. Another semi-automatic solution can be found in figure 2.8b, which is the Moorex developed by MacGregor. This system can easily bring tension to the mooring line once it is connected and can adjust its tension based on the vessel movements. Releasing the mooring line is automated once a signal is given by the operator [60].

(a) A capstan with quick release hooks from Trelleborg AB, to ease the releasing of the ropes [3].

(b) Moorex, the semi-automatic mooring solution from MacGregor [60]

Figure 2.8: Semi-automatic mooring solutions.

Features

- The mooring mechanism is easy to integrate. It only required a few components, capstans and ropes, of which most of them are already available. There is no need for additional integration of software.
- There is no need for any sensors signals, since the operation is manually executed. This makes the mechanism relative robust.
- By selecting the correct rope type and capstan, the mechanism is easily adaptable for different configurations.

Limitations

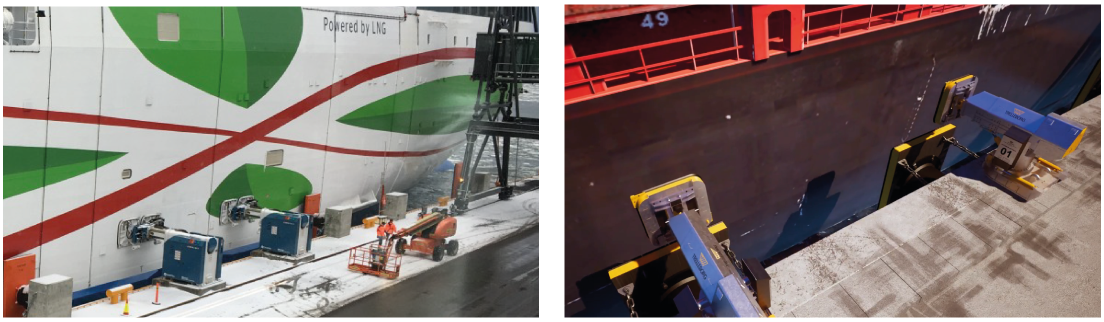
- The mooring procedure takes relatively long, since all the mooring lines has to be moved and secured manually. The exact mooring time is depending on the vessel type and can vary between a couple of minutes for smaller vessels up to 1.5 hour for large tankers [21].
- Since multiple lines have to connected to ensure proper mooring, the mooring procedure requires generally multiple ferry crew members.

- Manual operation can cause risks for the ferry crew and perhaps even passengers. Especially for large vessels where the dimensions of the ropes and the forces on it are large, accidents have happened more than once. For instance people getting intertwined in the ropes or by snapback from ropes that are not properly secured [23].

- Manual operation is sensitive to human error. Humans do make mistakes relative easily. This can be caused by various reasons such as distractions, tiredness or physical problems.

Vacuum mooring

One of the innovate ways of vessel mooring, is mooring by using vacuum suction cups. In 1999 Cavotecs first more MoorMaster™, shown in figure 2.9a entered the market [21]. Trelleborg followed in 2017 with the launch of the AutoMoor, which can be seen in figure 2.9b [2]. The working principle for both is equal. A vacuum is created between the mooring mechanism and the ship. One mechanism is sufficiently strong to keep smaller vessels in position, simultaneous use of multiple mechanisms, vessel over 300m can be moored [21]. The holding force of the Cavotec and Trelleborg system is ca. 200 kN per suction head. Per mechanism either one or two suction cup can be installed. To handle the motions from the vessel, the suction cup is supported by multiple hydraulic cylinders which makes its flexible in three dimensions. It the case of larger height differences the mounts can lose itself for a while, to secure itself again at another height. This is especially useful during the transshipment of heavy goods which affect the draft of the vessel significantly.



(a) The MoorMaster™ from Cavotec [21]

(b) The AutoMoor from Trelleborg [81]

Figure 2.9: The vacuum based mooring mechanisms.

Features

- The connection time is short. Trelleborg claims to moor the vessel within a minute and Cavotec even says to achieve this in less than 30 seconds. Also the disconnection time is short, comparable to the connection time.

- The mechanism can be used for a wide range of vessel types. When the size of the vessel increases, the amount of suction cups and the total amount of mooring mechanism can easily by multiplied to provide enough mooring strength.

- Mooring can executed without any human intervention. This decreases the chance of accidents for the ferry crew. Possibly is even decreases the amount of crew required on the ferry at all.

Limitations

- The mechanism requires a relative large flat area, about 3m^2 per suction cup, in order to create a vacuum underneath the suction cup. This area is not always available. Especially on smaller vessels this might be on issue.

- Both Trelleborg and Cavotec mechanism have quite a large footprint, ca 2m x 2m (l x w). Because of the the required flat area, the system is generally mounted in the side of the vessel. Therefore there should be a quay available on the side of the vessel with sufficient space available to install the system.

Magnetic mooring

Mampaey has developed a mechanism which appears quite similar to the vacuum mechanisms. However the plates are not connected to the vessel by air pressure but by magnetic attraction. This mechanism called the *intelligent* Dock Locking System ®(IDL®) is shown in figure 2.10. The IDL®uses an array of magnets which are moved by multiple hydraulic cylinders. The stoke and pressure in these cylinders can be measured which enable to determine to force caused by vessel movements. The holding force of one system is 320 kN in sway and 130 kN in surge [16]. The first two systems have just been installed in Woolwich to moor a new build ferry here. This ferry is not sailing yet, so the system has not been proven until now [50].

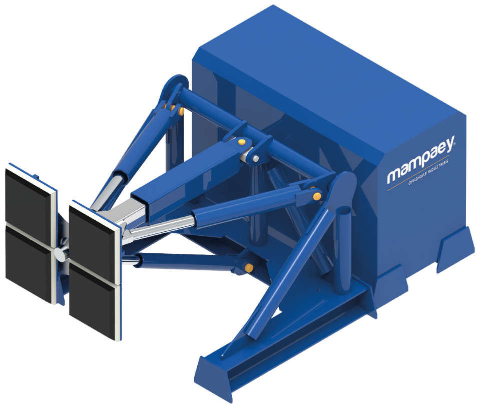


Figure 2.10: The *intelligent* Dock Locking System ®from Mampaey Offshore Industries B.V. [16].

Features

- This mooring mechanism claims to be the fastest solution. Mooring should be finished in 10 seconds, unmooring even within 5 seconds
- Human intervention for the mooring procedure is excluded which is beneficial for the safety of the ferry crew. Possibly this can result in a decrease of the mount of ferry crew required.

Limitations

- Just like the vacuum mooring mechanism, also the magnetic mooring mechanism requires a flat area the hold on to of almost $3m^2$. This area is not always available. Especially on smaller vessels this might be on issue.
- The power supply behind the magnetic pad comes with substantial dimensions as well. It has a footprint of 2.5m x 3m (l x w) and the mechanism weighs over 5500 kg. Because of the the required flat area, the system is generally mounted in the side of the vessel. Therefore there should be a quay available on the side of the vessel with sufficient space and foundation available to install the system.

Mechanical solutions

Various mechanical solutions had been developed. Varying form concepts to actual working products and from small mechanisms to large installations. A relative small, but effective solution, is operational in Langweer (NL). The mechanism shown in figure 2.11a is developed by Bijlsma Wartena. The hydraulic cilinder is mounted on the front of the ferry, which is equipped with a bigger ball at the end of the cylinder. Once its arrives at the port, the pole is lower into the V-shape structure installed on the quay. The pole locks because of the ball mounted on the end of the pole which is larger than the gap in the V-shape. With the hydraulic cylinder the mooring mechanism enable to pull itself against the shore. Unmooring is achieved by simply pulling up the pole again.

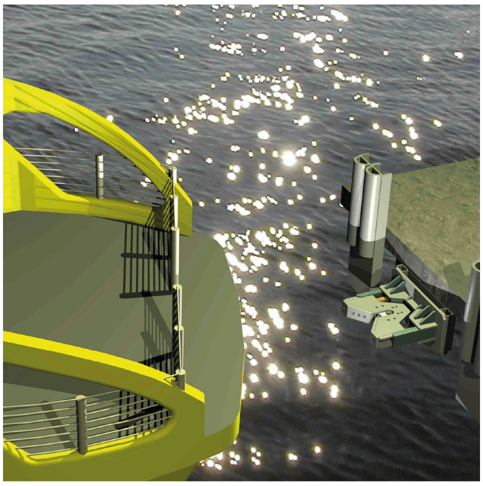
Another mechanical solution is the one developed by MacGregor or TTS. This is purposed to serve larger vessels compared to the one from Bijlsma Wartena. These can be seen in figure 2.11b and 2.11c. Both working principles are more or less equal. Once the vessel the is in position, the system is activated by a push on the button. The mooring arm moves to the programmed position and then moved downwards to placed the beams eye over the vessels build-in bollard. To release to vessel, a crew member needs to push a button after which the mechanism retracts again [60],[11].

A last interesting mechanical mooring concept is the Smartlander™from Momentum Marine. This a one man company which designed the mechanism shown in figure 2.11d. The idea of this mechanism is that the vessel can directly sail into the Smartlander, after which it locks. Unlocking can be executed by a simple push button. This solution does seem most beneficial for smaller vessel such as passenger ferries. However, this is still a concept and was never actually build [69].

(a) The mooring mechanism from Bijlsma Wartena in Langweer.

(b) The auto-mooring system developed by MacGregor [60].

(c) The grip-based auto-mooring system from TTS [11].



(d) The Smartlander designed by Momentum Marine [69].

Figure 2.11: Multiple mechanical mooring mechanisms

Features

- All mechanisms are automated and can operate without human intervention. This decreases the chance for dangerous situations for the ferry crew and possibly even decrease the amount of crew required on board of the ferry.
- The power demands for the mechanism is expected to be less compared to vacuum or magnetic mooring. This seems reasonable since the holding force is in this situation delivered by the material strength instead of electrical power which is the case for vacuum and mechanical mooring.

Limitations

- The mooring system of Bijlsma Wartena and Smartlander is designed for a relative small ferry, sailing in the shallow lakes in Friesland. The tidal difference and the waves in these environments are generally small.
- Both the auto-mooring system form TTS and MacGregor have been designed install on the side of the vessel because of the large foot print of the system. The port should have sufficient space available for this installation.
- These mechanical mooring mechanisms have a smaller damping ability compared to the vacuum and magnetic mooring mechanisms, which are supported by multiple hydraulic cylinders.

2.2.3. Conclusion

The goal of this section was to gain insight in the mechanisms that are currently available for charging and mooring of electric vessels. It was seen that a variety of mechanisms has already been developed for both functions. For charging mechanisms there is not such thing as standard solution yet. All systems that have been developed, where designed for a specific vessel or fleet which can easily be noticed when inspecting the specifications of the mechanism. This way of developing causes that every system comes with its own features and limitations. When an existing charger is not suitable for a certain vessel, a new charger is developed which has the correct features to charge this vessel. This charger probably again with some limitations, which are not relevant for this, but are restricting for a new project. Furthermore, all systems that have been installed are the first of their kind and come along with some unforeseen failures. Charging mechanisms for electric are a relative new research field which is only operational for a couple of years. It is likely the after some years, one preferred and more standardized system rolls out, and generalizes this market field....

In the entire shipping industry manual mooring lines are most often used for mooring of vessel. However, for shuttle ferries which need to charge in a restricted amount of time, this way of mooring is to slow. For these cases, the vacuum mooring systems are the most commonly used. Some other mechanisms, such as a magnetic mooring system or various mechanical mooring systems have been developed as well. However, the are rather one of a kinds products and not standardized products yet. In the follow chapter, the case study of BC Ferries will be executed. Here it will be checked if one of the existing mechanisms would be suitable for this case, of why it is not.

3

Case study: BC Ferries

This case study is executed to find a charging and a mooring mechanism for the BC Ferries vessel. In order to find these mechanisms, the design method from [24] is followed. The process of this case study will be evaluated afterwards to set up the guideline for finding a charging and mooring mechanism for electric vessels. In section 3.1 the first step of the design method is executed. The aim of this section is to gain insight in the main and sub objectives of this case study. Then, in section 3.2, the functions which both mechanisms should fulfill are discussed. After these sections the orientation phase is completed and limitations should be determined in the following phase. This is done in section 3.3 and 3.4. In section 3.3 the requirements are determined which should be fulfilled in order to be a suitable product. In section 3.4 the preferences are determined which will be used to check if one systems is more desirable over another. After this phase the gap between the exiting mechanisms from chapter 2 and the determined requirements should be clarified. This is done in section 3.5. Section 3.6 till 3.8 cover the design of a new system. The focus of this design will be to cover the gap that was defined. A conclusion of the case study if provided in section 3.9.

3.1. Clarifying objectives

The goal of this section is to gain insight in the objective of the case study. To do so, an objectives tree is constructed. In this tree, the main objective is stated on top of the tree with the sub-objectives listed underneath. These sub-objectives are conditions that should be satisfied in order to accomplish the main objective, or to improve the result. The objective tree of this case study can be found in figure 3.1. The main question asked here is: *Why do we want to design a charging and mooring mechanism?*. Since this is the objective of this case study. Looking at the objective tree, one can see that these systems do not have a goal on its own. This makes sense, since a charging mechanism or a mooring mechanism does not have a purpose as a standalone product. The main objective is to enable the BC Ferry to sail on electric power. This is desired by BC Ferries due to the advantages of electric sailing over diesel propulsion. For instance the decreased exhaust of GHG and the decreased noise and vibrations. This decreases the noise pollution to the environment and higher sailing comfort for the passengers. Realization of electric sailing comes with a lot of necessities such as an onboard battery pack, an electric engine and a charging system. Most of these necessities are beyond the scope of this research and therefore excluded from the objectives tree. The one necessity that is the in the scope of this project is the charging mechanism. This is necessary to provide power that can be stored in the vessel battery. To improve the functionality of the charging mechanism, the vessel propeller should be turned off during charging. This will result in a decrease of energy costs, less exhaust of GHG and a reduced size of the charging system. Herefore, it is necessary to moor the vessel while charging, such that a mooring mechanism is required.

Having set up the objectives tree, a clear insight is obtained in the objective of this case study. Now that it is clarified why a charging mechanism and a mooring mechanism should be found for the BC Ferries, it should be determined what exact functions these systems should fulfill. This will be discussed in the following section.

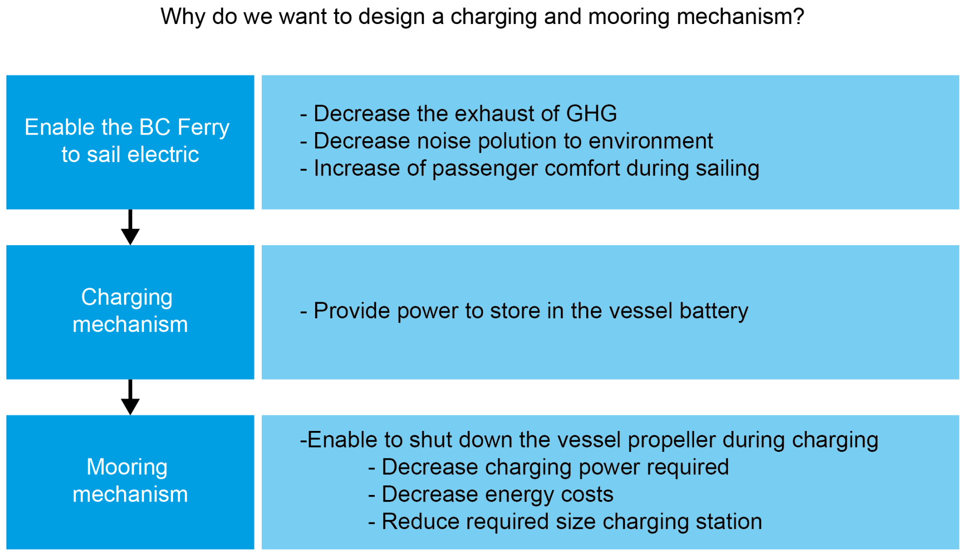


Figure 3.1: The objectives tree of the case study to clarify the object of this case study.

3.2. Establishing functions

Now that the objective of the design is clarified, the functions should be established. This is first done by the black box approach. For this, the mechanism is pictured as a black box which turns the given input into the desired output. The black box for this case study is shown in figure 3.2.

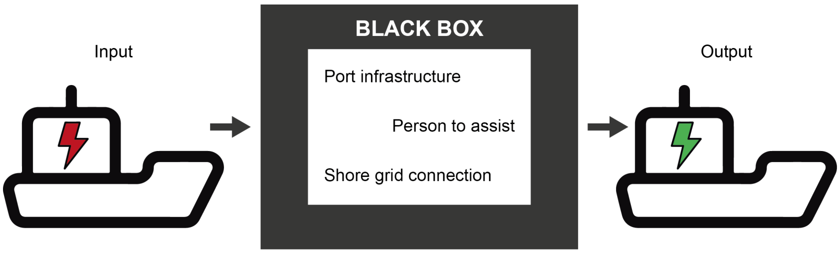


Figure 3.2: The blackbox of this case study, where the black box presents the charging and mooring mechanism performing their functions.

Taking it down to the basics, the input is a the ferry arriving in the port with an empty battery pack. The output of the system is a ferry leaving the port with a full battery pack. To realize this transformation from input to output, the charging and mooring mechanism is required. Other objects are present during this operation. These are not defined as input or output since they are not transformed form one state into another by the system in the black box, but these can support the functionality of the systems in the black box. As can be seen in figure 3.2 this includes the port infrastructure such as the ramp, which is fixed at the shore side and adjustable in height on the water side. The infrastructure also includes the wind walls on both sides of the vessel rear end. These are firm structures to which the vessel can sail into and this way stay approximately the same position. A connection to the power grid is available, which can supply enough power to the charging mechanism. Furthermore, there is one member of staff available to possibly the charging or mooring system or both.

To realize the conversion from input and to output, the main function of the charging mechanism is to charge the vessels battery. However, there are multiple functions for the system in order operate properly. To determine all sub-functions, a functional breakdown structure (FBS) is constructed. The FBS is functional-oriented and not products related. Therefore, it does not include working-principles but only functionalities [31]. This is important since there is not system defined yet, so not working principles can be defined either. The FBS of the charging mechanism is shown in figure 3.3. To charge the vessel, the charger should be connected to the vessel. This can either be a physical or a wireless connection. The charging mechanism recognize some kind of signal to activate the system and make the connection afterwards. The charging sys-

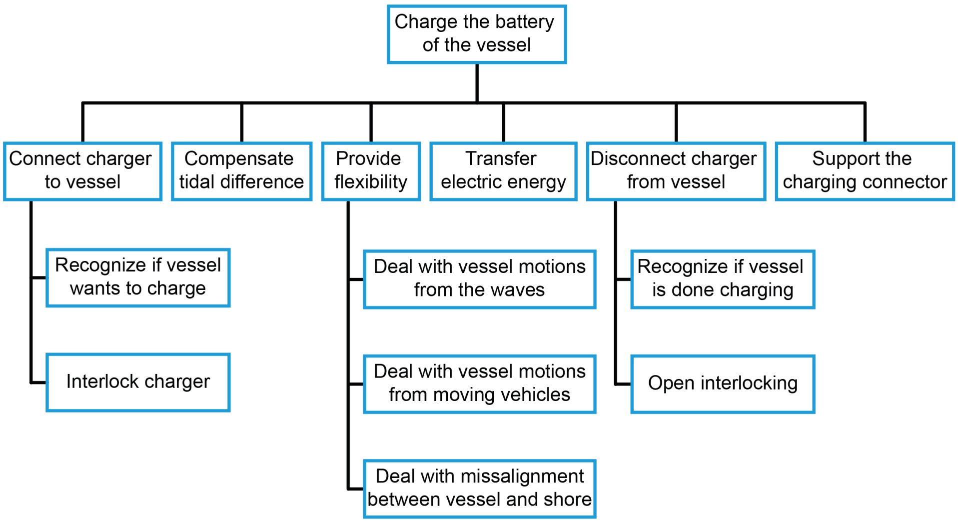


Figure 3.3: The functional breakdown structure of the charging mechanism.

tem should be able to operate independent of the current tidal difference, so this should be compensated. While charging, the vessel should provide flexibility, since the vessel will move during charging due to multiple causes which can be seen in the FBS. Of course, electric energy should be transferred form the shore grid to the vessel battery. Once the vessel is finished, the charging mechanism should recognize this and disconnect the charger from the vessel. Furthermore, the charger should contain a structure that is able to support the load of the charging connector which can be for example a plug on a cable or an inductive coil.

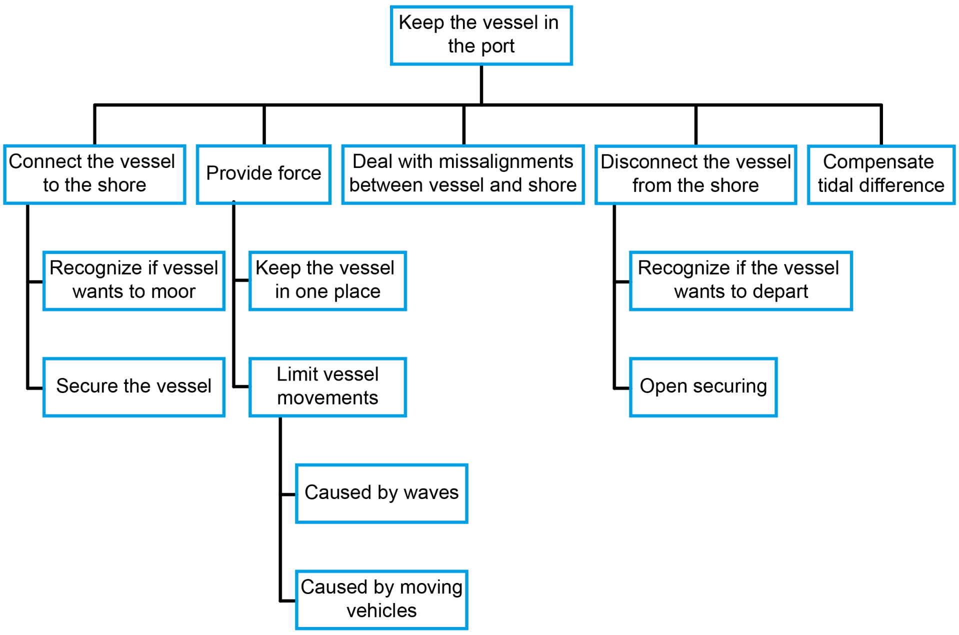


Figure 3.4: The functional breakdown structure of the mooring mechanism.

The main function of the mooring mechanism is to keep the vessel in the port, such that the vessel does not need to use its propeller. Also for this mechanism a FBS is constructed to obtain an overview of all subfunctions that support this main function. This can be found in figure 3.4. To keep the vessel in the port, it should be connected. To do so, the mechanism should be able to process a signal when the vessel is read to moor an connect it afterwards. The mooring mechanism should provide sufficient force to keep the vessel in one spot and let it not sail away. But it should provide also additional force to limit the movements of the vessel which will be caused by the waves are by the transshipping traffic. It might occur that the vessel does not always align with the port perfectly. The mooring mechanism should be able to deal with this and still connect to the vessel. When the vessel wants to leave, this should be recognized by the mooring mechanism which will then disconnect the vessel. The mooring mechanism should be able to operate independent of the tide level. There the mooring mechanism should compensate for the tidal difference is some way.

Comparing figures 3.3 and 3.4 a great similarity between the functions of both mechanisms can be found. Therefore it seems reasonable to argue that both mechanisms can be incorporated in one system. However, as seen in the previous chapter, this has not been done until now. The main issue to do so, is caused by one conflicting function between both systems. Where the charging mechanism should provide flexibility to deal with the motions of the vessel, the mooring mechanism should provide force the decrease these motions. One could argue that if the force is large enough, there is no need to provide flexibility any more. However, unless the vessel is dry docked, vessel motions will not be completely eliminated and therefore the charging mechanism should always be more flexible compared to the mooring mechanism. This makes it hard to combine the charging and mooring mechanism into one system. Since the time available for this research is only limited, it is not feasible to design two new systems in the research. Therefore the mooring mechanism is form this point rejected form the scope of the case study.

3.3. Setting requirements

In this section the requirements for the charging mechanism are determined. In 3.3.1 the requirements concerning the mechanical aspects of the system will be determined. This covers the conditions which mainly influence the mechanical aspects of the design such as, the vessel design, the port layout and the environmental conditions. Next, the electric aspects are discussed in 3.3.2. The last subsection, 3.3.3, covers all user requirements such as safety, level of automation and financial limitations. The goal of this section is to set up a list of requirements to determine which design could be suitable for the BC Ferry, but also the gain insight in the relation between the different requirements. In the BaCO research it already appeared that multiple requirements can be strongly related [27]. When the relation between these is structured, a better overview of the possibilities is created. A complete list of the requirements is provided in appendix B, in this section it will be explained how these requirements have been determined.

3.3.1. Mechanical requirements

The mechanical requirements concern the limitations with respect to the space available on the vessel and in the port, but also the weather conditions to which the systems and the vessel will be exposed. It was chosen to determine these first, since these aspects are relatively easy to determine without complicated calculations. Moreover, these limitations are often fixed and hard to modify.

Operating environment

The vessel will initially be sailing on two routes between the coast of Canada and Vancouver. These are route 18 and 25, of which their location in shown in figure 3.5.

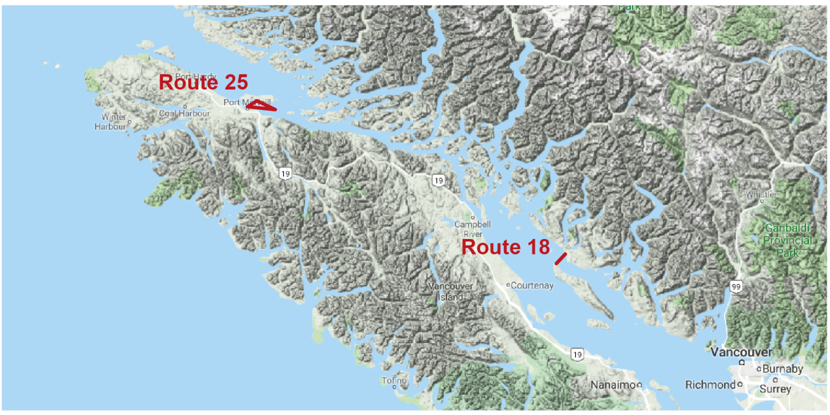


Figure 3.5: The location of route 18 and 25 where the BC Ferries will be sailing.

Since the mooring and charging mechanism will be operating outdoors it is of major importance that both are suitable to operate properly in the local weather conditions. This concerns the precipitation, outdoor temperature, wind- and wave conditions. To evaluate the local precipitation and outdoor temperature, the statistics published by the Canadian Government are used. Two weather stations have been analyzed, namely weather station Powell River A and Port Hardy A. These are respectively located close to route 18 and route 25. For both stations weather data is available for more than 60 years in history. Extreme values of these historical data have been used to set a benchmark for the requirements. These are shown in table 3.1. In this table also the wind force requirements are given. These are equal to the wind force for the ferry design and have been defined by BC Ferries. Equal applies to the tidal difference. The worst case scenario of the five ports has been taken as a requirement, which is the tidal difference in the port Blubber Bay on Route 18.

	Highest temp. (°C)	Lowest temp. (°C)	Most precipitation (mm/month)	Most snow on the ground (cm)	Max. wind force normal operation (Bft)	Max. wind force restricted operation (Bft)	Tidal difference (m)
Extreme Powell River A	35.5	-16.7	80	48.3			
Extreme Port Hardy A	33.3	-14.4	153.8	33.4			
Requirement	**35.5**	**-16.7**	**153.8**	**48.3**	**7**	**8**	**7.1**

Table 3.1: Extreme weather conditions measured at Powell River and Port Hardy and the requirements for the charging and mooring mechanism to be designed [72], [71].

The waves in the operating environment are important to take into account. The wave spectrum of Powell River is used, which is shown in figure 3.6. It is reasonable that the wavespectrum in the other ports will be comparable to Powell River since they are all equal or more enclosed by land. The wave height and frequency show that the waves in the port are relatively small, which makes sense since the sailing area is enclosed by land. Therefore, waves are mainly created by wind and do not much space to develop. The wind direction in the operating environment is varying in each direction. However, as can be seen in figure 3.7, the wind comes primarily form the west or the east. Since the waves are induced by the wind, this also presents the common wave directions.

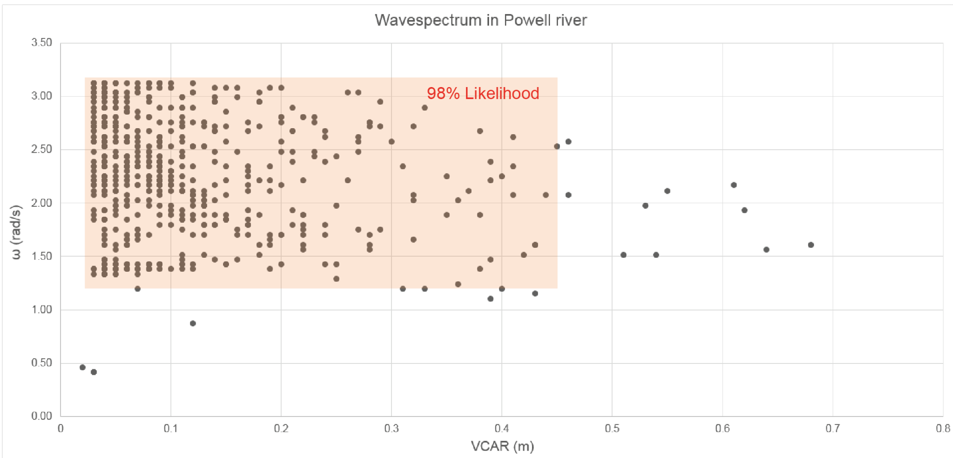


Figure 3.6: The wavespectrum from Powell River, Britisch Columbia [70]

Another important aspect of the operating environment is the layout of the ports where the vessel should dock. To ease the implementation of the electric vessel, only minor changes are allowed to the infrastructure of the ports. The infrastructure of the ports, and the ferry docked in it, is shown in figure 3.8. Here it can be seen that the layout of the ports is more or less standardized but still varying.

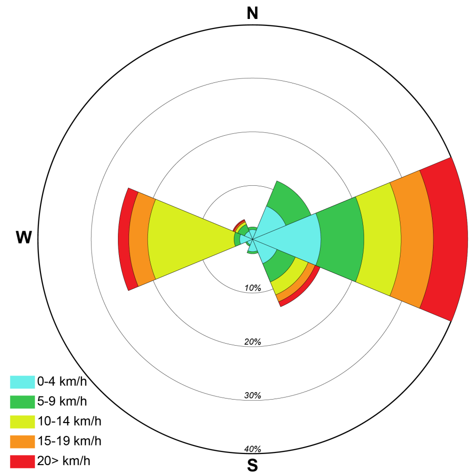
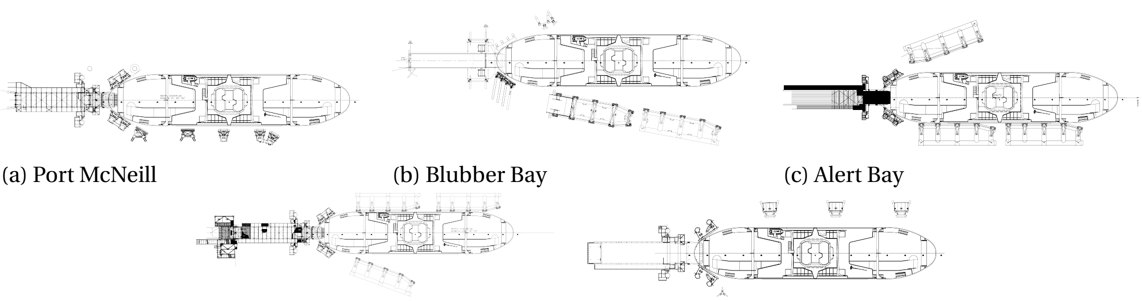


Figure 3.7: The windrose of Port Hardy showing the occurrence of each wind direction and the windspeeds from these direction. Constructed with data from [73].



(a) Port McNeill (b) Blubber Bay (c) Alert Bay

(d) Sointula (e) Westview

Figure 3.8: The layout of the ports on route 18 (a and b) and route 25 (c, d en e).

The greatest similarity between all ports are the ramp and the wind wall. Besides there are some dolphins located in the ports on different locations, which are the structures next to the vessel as shown in figure 3.8. Since only some of these are fixed and others are floating, these are not suitable for the installation of other mechanisms. The free area around the ferry in the figures in 3.8 cannot be occupied by any installations, since larger vessels are supposed to dock in the same ports. These could be obstructed by the new installations. The length if the ramp varies per port, but is approximately 25m. In figure 3.8 all vessels are perfectly aligned with the port and the vessel center line is col-linear with the ramp center line. In actual operation misalignments between the vessel and the port will occur due to various causes such as human steering mistakes or forces from the water current. The charging and mooring mechanism should be able to deal with $\pm 7^c irc$ degree deviation between the ramp and vessel center line as illustrated by figure 3.9. It is assumed that the vessel is always touching both wind wall in any case.

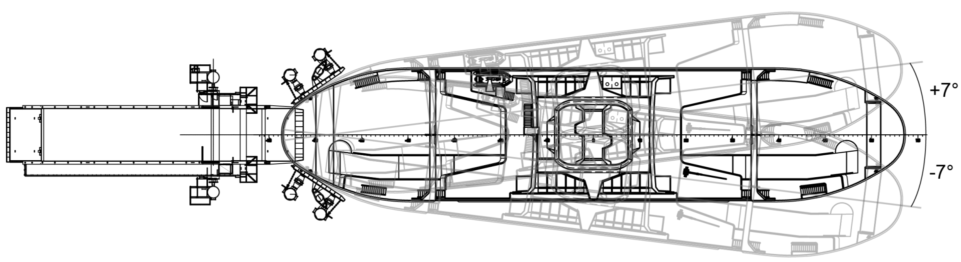


Figure 3.9: The alignment variations of the vessel with respect to the port that should be covered by the charging and mooring mechanism.

Vessel design

Since the vessel of BC Ferries is not originally designed to sail electric, this has not been taken into account in the design of the vessel to a large extend. Since it was already announced that the vessel should be converted into an electric vessel some day, space for additional batteries has been saved. However, a location for the charging installation was not included in the design. Since the available space on the vessel is limited and additional weight on the vessel can have a large impact on the sailing behavior, it seems logical to assume that the socket should be placed on the vessel. This is generally the smaller component for a plug-socket connection. Furthermore, it is important that the onboard charging system does not obstruct the vessel for vehicles and passengers moving on and of the ferry. As can be seen in figure 3.10, the area where people and vehicles are moving cover a large part of the vessels rear end.

As already mentioned in 2, IEC developed a standard for shore connection systems which prescribe that "*Plugs and socket-outlet connection shall be in areas where personnel will be protected in the event of an arc flash as a result of an internal fault in the plug and/or socket-outlet by barrier and access control measures. These measures shall be supported by access control procedures*" [48]. The charging mechanism will induce a inductive field in its surroundings. Passengers and staff should be protected from this such that their exposed is within the defined limitations.

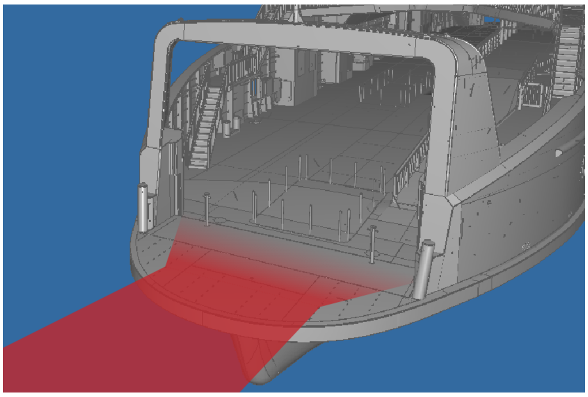


Figure 3.10: The rear end of the vessel where passengers and vehicles transship between the ferry and the shore. The areas that are marked red must remain free for traffic on and of the vessel.

Ship motions

A sea keeping analysis is done to predict the motions of the vessel caused by waves. The motions of the vessel are important to predict, since these determine the required flexibility of the charging system and the demanded mooring force of the mooring system. The modeling method used is the strip theory, which considers a ship to made up of a finite number of transverse two-dimensional slices which are rigidly connected to each other. This method is only valid for long slender bodies (l/b≥3) with a constant speed, which is the case for the BC Ferry [53]. Input for this analysis contains a model of the hull shape and one or multiple loading conditions. An impression of the hull shape can be found in Appendix A. Important to notice, is that the vessel is symmetric in both x- and y-direction. Therefore only a quarter of the wave directions have to be calculated. Ten possible loading conditions have been determined by Damen during the development of the vessel [14]. The lightest and heaviest operational loading condition are adopted for the sea keeping analysis to determine the vessel motions. The output of the simulation is the response of the vessel with respect to the wave conditions, graphically shown in a Response Amplitude Operator (RAO). For each of the six degrees of freedom a RAO is developed, which can be found in appendix C. Here, the predicted movement of the vessel in each direction can be found as a function of the wave frequency in meter per meter wave height of for rotation in deg per meter wave height.
Comparing the two load cases, it can be seen that the largest movement occur for the heaviest load case. Therefore the heaviest operational condition assumed to present the worst case scenario. The results of these RAOs present the motions in the center of gravity of the vessel. However, as already determined before, it is more likely that the charging and mooring mechanism will be installed at the rear end of the vessel, due to the port infrastructure. Therefore the vessels at the location of the bolder are calculated as well, which are located on both sides of the vessel rear ends as can be seen in figure 3.10. To obtain absolute values of the expected motions, the boundaries of the 98 % likelihood of the wave spectrum from figure 3.6 is applied. This

included wave heights of 0.45m or less, and wave frequencies of 1.25 Hz of larger. The results can be found in figure 3.11. Since the bolder is located on one side of the vessel, symmetry cannot be applied in this case and therefore eight wave directions, equally spaced over 360°, are plotted. As can be seen, the largest movements in y and z direction occur for waves either at 270°. The largest movement in x direction however, occur with all diagonal waves at 45°, 135°, 225° or 315°.

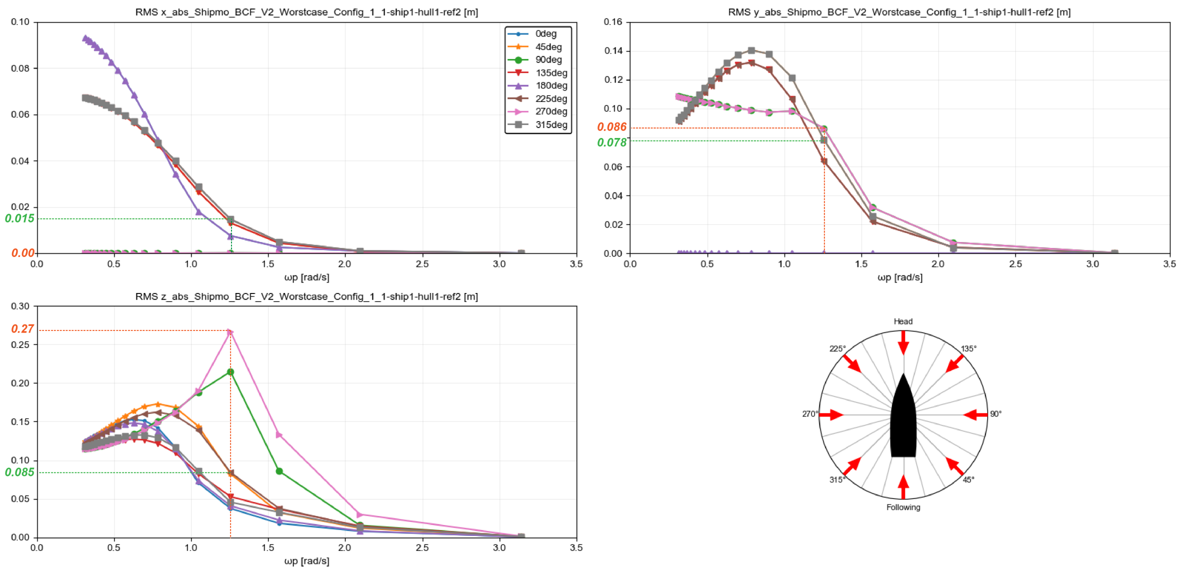


Figure 3.11: The predicted motions of the bolder for a wave height of 0.45m and ω=1.25

3.3.2. Electric requirements

The electric requirements are only applicable to the charging system. These are placed secondly since the determination of these requirements is generally some more time consuming compared to the mechanical requirement. Setting requirements in this order prevents from doing the time consuming calculations first, while afterwards it might turn out that electric sailing is not feasible due to mechanical constraints. Since some of these calculations have already been executed by the BaCO project at Damen, these requirement have been adopted.

Power demand

The power required to charge an electric vessel depends of multiple parameters, which can be divided basically in two groups. The first group are the variables that determine the energy used by the vessel while sailing such as its speed, loading conditions and the sailing time. The second group are the parameters that the time available for charging, such as the connection time, total time at the port and the charging strategy. The power demand of the charger for the BC Ferry is determined to be 2 MW for route 18 and 4 MW for route 25 [27]. This is calculation is based on the sailing profile as it is nowadays with the current ferry. Adjustments to the schedule, such as slower sailing speed or longer stopping time, will reduce the power demand. However, this is out of the scope of this research. Therefore the worst case scenario is chosen and the power demand will be restricted to 4MW.

Electricity supply

For the electricity transfer, one can chose for either low voltage (LV), max 1000VDC, or high voltage (HV). In the shipping industry HV implies a 3.3 kV, 6.6 kV or 11 kV connection. For both HV and LV connections a standard was developed by IEC as already discussed before [48], [49].The implications of choosing or a HV or LV connection are quite significant will be described below.

LV shore connection

For the LV scenarios both AC and DC can be considered. Shore connection is supposed to provide the power for vessel switchboard and charge the battery at the same time. To store electricity in a battery, the power supply should always be DC. The switchboard can be operating on AC or DC connection. In the case of an

DC switchboard it is advised to consider only a DC shore connection, since there would be no additional benefit for AC power supply and an onboard rectifier would be required. In the case of an AC connection, one should install an onboard rectifier to charge the batteries. However, power supply to an AC switchboard is in this case straightforward which should otherwise be created by an onboard inverter. Since the switchboard of the BC Ferry is operating on DC, only the DC shore connection will be considered for this case.

The main advantage of a LV shore connection is the simplicity of the onboard grid which is shown in 3.12. The power supplied from the shore can be directly connected to the switchboard, from where it is further distributed to the vessel batteries. For this scenario there should be a transformer and a rectifier installed on shore. However, the space available here is not a limiting factor as it is on the vessel. Another advantage is of the LV connection is that the required safety measures are less with respect to HV voltage operation. Especially for manual operation, this could play a major role.

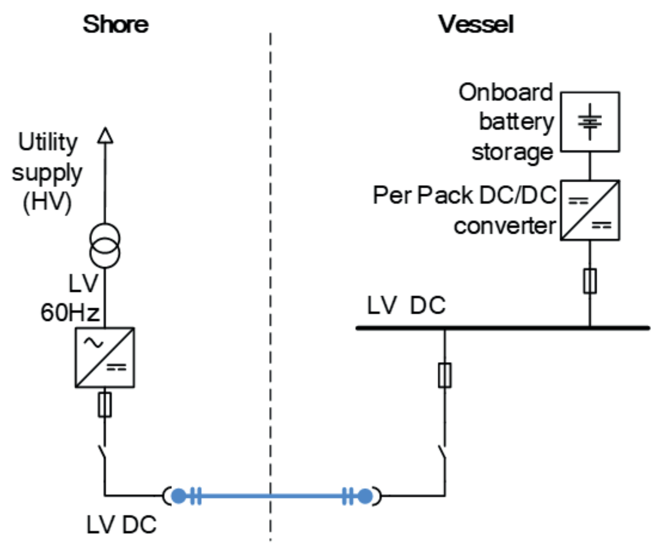


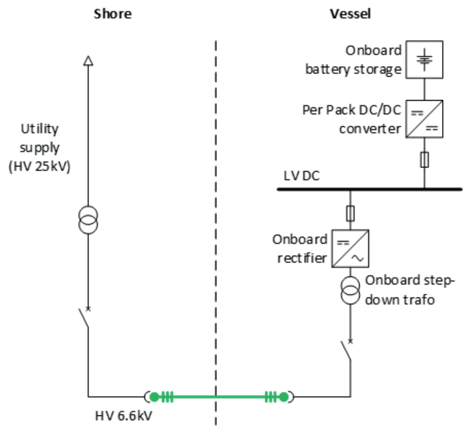
Figure 3.12: Schematic overview of the LV shore connection [27]

A significant disadvantage of a LV connection is the relative thick cable required due to the high current flow. This decreases the flexibility of plug and makes it therefore more sensitive to the movements of the vessel while it is charging. The cables required are discussed in more detail below.

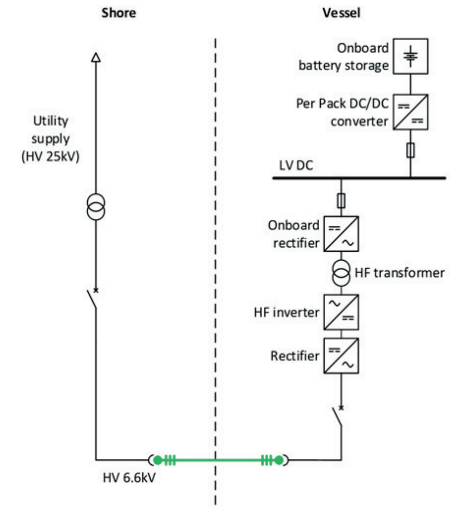
HV shore connection

The HV link considered is a 6.6kV three-phase link, which is the standard HV connection as described in IEC 80005-1 [48]. For HV only the AC case is considered in practice since transformation is only possible in AC, which is required to connect the shore power to the LV switchboard. DC power supply would require an additional rectifier on shore and an onboard inverter, without additional benefits. A schematic overview of the HV shore connection is given in figure 3.13a. For this scenario the power supply should be onboard transformed and rectified to be compatible with the onboard switchboard. The size and weight of the this transformer are significant, about 2 t/MW and at least several cubic meters, which makes it harder to fit into the existing vessel and is disadvantageous for the energy usage during sailing. The size of the transformer can be reduced significantly by using a high frequency (HF) transformer. In this case the power supply should first be rectified and inverted into a HF link, which can be transformed afterwards as shown in figure 3.13b. However, this will result in a lower efficiency due to the increased amount of conversion stages.

The main advantage of the HV power supply, is the relative small current flow, which is only 350 A. Therefore the cable thickness is reduced significantly. This comes with an increased flexibility of the cable. In the next part, the cable options for both the HV and the LV scenario are discussed.



(a) Schematic overview of the HV shore connection [27].



(b) Schematic overview of the HV shore connection with a HF transformer [27].

Figure 3.13: The options for a HV shore connection.

Cables

The required cable is primarily restricted by the current that should flow through. Bureau Veritas has developed a standard to determine the correct cable for a certain application [84]. The table from figure 3.14 is copied from this standard.

Table 8 : Current carrying capacity, in A, in continuous service for cables based on maximum conductor operating temperature of 90°C (ambient temperature 45°C)

Nominal section (mm^2)	Number of conductors		
	1	2	3 or 4
1,5	23	20	16
2,5	30	26	21
4	40	34	28
6	52	44	36
10	72	61	50
16	96	82	67
25	127	108	89
35	157	133	110
50	196	167	137
70	242	206	169
95	293	249	205
120	339	288	237
150	389	331	272
185	444	377	311
240	522	444	365
300	601	511	421
400	dc: 690 ac: 670	dc: 587 ac: 570	dc: 483 ac: 469
500	dc: 780 ac: 720	dc: 663 ac: 612	dc: 546 ac: 504
630	dc: 890 ac: 780	dc: 757 ac: 663	dc: 623 ac: 546

Figure 3.14: Current carry capacity, in A, in continuous service for cables based on maximum conductor operating temperature of 90°C (ambient temperature 45°) [84].

In this table, the maximum current flow is given for a certain conductor cross sectional area (CSA) and the amount of conductors in a cable. It can be seen that the maximum current flow through a cable increases when the conductor CSA increases, but that the allowed current per conductor decreases when multiple conductors are joined in one cable. This is can be ascribed to the heat dissipation which is less for multiple cores in one cable, compared to separate cables. The table from figure 3.14 is meant for a maximum conductor operating temperature of 90°. This is the standard required for the for cables that are used for shore power supply according to [48] and [49]. Therefore, the other tables from [84], for different conductor temperatures, are not included in this report. The standard ambient temperature is 45°C, however as seen in 3.3.1 the ambient temperature is not expected to be above 35°C. A correction factor of 1.10 may be applied for this temperature difference, as can be seen in figure 3.15.

Maximum conductor temperature, in °C	Correction factors for ambient air temperature of:										
	35°C	40°C	45°C	50°C	55°C	60°C	65°C	70°C	75°C	80°C	85°C
60	1,29	1,15	1,00	0,82	–	–	–	–	–	–	–
65	1,22	1,12	1,00	0,87	0,71	–	–	–	–	–	–
70	1,18	1,10	1,00	0,89	0,77	0,63	–	–	–	–	–
75	1,15	1,08	1,00	0,91	0,82	0,71	0,58	–	–	–	–
80	1,13	1,07	1,00	0,93	0,85	0,76	0,65	0,53	–	–	–
85	1,12	1,06	1,00	0,94	0,87	0,79	0,71	0,61	0,50	–	–
90	1,10	1,05	1,00	0,94	0,88	0,82	0,74	0,67	0,58	0,47	–
95	1,10	1,05	1,00	0,95	0,89	0,84	0,77	0,71	0,63	0,55	0,45

Figure 3.15: Correction factors for various ambient air temperatures [84].

Another second correction factor that should be applied, can be found in figure 3.16. When a cable is intended for a short-time service, the current carrying capacity may be increased. Since the service time for the vessel charger will only be around 10 minutes, the 1/2-hour service values may be used. Since, cables for shore connection are in general cables with metallic sheath, one should use the left column to determine the corresponding correction factor to a certain conductor size.

1/2-hour service		1-hour service		Correction factor
Sum of nominal cross-sectional areas of all conductors, in mm²		Sum of nominal cross-sectional areas of all conductors, in mm²		
Cables with metallic sheath and armoured cables	Cables with non-metallic sheath and non-armoured cables	Cables with metallic sheath and armoured cables	Cables with non-metallic sheath and non-armoured cables	
up to 20	up to 75	up to 80	up to 230	1,06
21 - 41	76 - 125	81 - 170	231 - 400	1,10
41 - 65	126 - 180	171 - 250	401 - 600	1,15
66 - 95	181 - 250	251 - 430	601 - 800	1,20
96 - 135	251 - 320	431 - 600	–	1,25
136 - 180	321 - 400	601 - 800	–	1,30
181 - 235	401 - 500	–	–	1,35
236 - 285	501 - 600	–	–	1,40
286 - 350	–	–	–	1,45

Figure 3.16: Correction factors for short-time loads [84].

To gain insight in the optional cables for the BC Ferry charger, table 3.2 gives an overview of the cables that can be used to transfer 4MW and their properties. One should pay attention that power supply requires positive and negative pole, so the conductors should transfer 8 MW in total. The weight and bending radius of the LV cables have been obtained form Helkama Bica [13], the properties of the HV cables have been obtained from Nexans [68]. Note that the bending radius of the cables is the smallest radius is which the cable can be bend without being damaged. So, this does not assign any value to the force required to bend it this way and does only included ultimate strength. It does not take into account possible fatigue failures due to continuous deformation of the cable.

	Conductor CSA [mm^2]	# Conductors	Outer Diameter [mm]	Weight [kg/m]	Current Rating [A]	Correction factor temp.	Correction factor short-time	Corrected Current Rating [A]	# Cables Required	Weight [kg/m]	bending radius [mm]
LV											
	185	1	26.5	1.92	440	1.10	1.35	653	14	27	265
	240	1	30	2.53	522	1,10	1.40	803	10	25.3	300
	300	1	33.5	3.12	601	1.10	1.45	958	10	33.5	335
	185	4	60	8.22	311	1.10	1.45	461	5	40,1	600
	240	4	68	10.96	365	1.10	1.45	562	4	43.84	680
	300	3	68	10.32	421	1.10	1.45	671	4	41.28	680
HV											
	150	3	74.5	9	272	1.10	1.45	404	1	9	567
	95	1	33.5	1.8	293	1.10	1.20	386	2	2.6	252

Table 3.2: Characteristics of the cables that could be used for shore power supply of 4MW [13] [68]

Other requirements to the cable set by [48] [49] and [84] are that the maximum operating temperature shall not exceed 95°, the cable should be flame-retardant, and it should be resistant to oil, sea air, sea water and solar radiation. Furthermore, details on the required constitution of the power cable can be found in these standards.

For some charging systems that where discussed in chapter 2 glass fiber incorporated in the cable to enable data communication between the vessel and the shore. If this is desired, it is important that this is known before the development of the charger since this is affecting the cable selection. However, for BC Ferries this is not desired.

Connector

The basic requirements for the design of the plug-socket connection are included in IEEE80005-1 and IEEE80005-3. Here it is stated that:

- The plug and socket-outlet arrangement shall be fitted with a mechanical-securing device that locks the connection in the engaged position.
- The plugs and socket-outlets shall be designed so that an incorrect connection cannot be made.
- Plugs shall be designed so that no strain is transmitted to the terminals and contacts. The contacts shall only be subjected to the mechanical load which is necessary to provide satisfactory contact pressure, including when connecting and disconnecting.
- Each plug shall be fitted with pilot contacts for continuity verification of the safety circuit. For single plug connections, a minimum of three pilots are required. If more than one cable is installed an interlocking shall be used so that no cable remains unused.
- Support arrangements are required so that the weight of connected cable is not borne by any plug or socket termination or connection.

Both standards refer to a more extensive standard for the design of industrial LV- and HV plug-socket connections. For LV systems this is IEC 60309, but this covers only plug-socket connections with a rated operating voltage not exceeding 690 V and a rated operating current not exceeding 250 A [45]. Since the LV design of the BC Ferry charger would exceed both limits, this standard cannot be used. For HV voltage systems the is the IEC 62613, which covers plugs, sockets and ship couplers for an operating voltage up to 12 kV and an operating current up to 500A. In this standard numerous rules are described which a HV connector should satisfy such as construction requirements, material requirements and necessary safety requirements [47].

For LV operation of the charger, the connector should transfer a current of 4000A. There are two main options to realize this. First of all, there is the option of multiple connectors. Since the HV connector standard is only valid up to 500A, one should apply at least eight of these connectors. The other option is to use custom made, not standard, connector, which can handle a higher current flow. For the design of such a custom made connection, IEC 62613 still be used as a guidance. A important attribute of this standard is the tests that should be satisfied by a new connection. This includes among others, the 'finger-test' for both the plug and socket, the mechanical strength of the connection and the material properties in warm or humid conditions. These tests should also be executed for a connector which transfers higher current. An example of such a connector is one from the Cavotec APS from figure 2.5a. This is able to transfer 2000A [20]. The weight of the plug on its own is already 800kg. However this is mainly due to the working principle where the plug falls into the socket due to gravity, and not because do the electric requirements. Furthermore, if data communication between the vessel and the shore is desired there should of course also be one or multiple fiber contacts in the connector to enable this. But since this is not desired for the BC Ferry, this is no requirement for the connector.

3.3.3. User requirements

The previous set of requirements have been set to determine what the limitations are for producing a physically feasible product. The user requirements, meanwhile, can be described as the requirements which make the mechanism an attractive product for a customer. These should generally be determined in proper consultation with the customer. Multiple subjects will be discussed below, and values will be given as far as known.

Connection time

The connection time for both the charging and the mooring mechanism is restricted to 30 sec. It is assumed that the charging mechanism can only connect after the vessel is being moored. This connection time was incorporated in the operational profile and so 4MW is sufficient power supply for this connection time. Also the disconnection time is limited to 30 seconds for both mechanisms.

Level of automation

From the state-of-the-art study in chapter 2, basically three levels of automation can be distinguished. These are:

- Manual. The system requires physical human interaction to operate. It can be that the system is mechanically supported to lighten the physical effort, but it cannot function without any physical human interference.
- Automated. The system requires human input, but this does not included any physical effort. This could for example be an operator who pushes a button to activate the system, after which the connection is made automatically.
- Autonomous. The system does not require any human interference to operate. An example of this is a system which registers if the vessel is in the port by sensor signals, after which it connects automatically.

The both the charging and mooring mechanism are preferred to be automated, but this is not mandatory in the opinion of BC Ferries. However, the physical abilities of the personnel are limited. Only one member of staff is available to assist the mechanism and it may not require any heavy lifting.

Since the purpose of this research is to create generic solution, which can be used for other vessels, the charging mechanism is required to be automated. An automated mechanism is considered to be more future proof with respect to handling convenience and safety measures. The mooring mechanism is not necessarily completely automated but might also be manually operated. The main goal of the mooring mechanism is rather to make it effective. If this can easily be automated, this is of course not excluded. However, if automation makes the design over complicated, it may also require basic human assistance. The maximum force that may be required from the operator restricted to 50N.

Safety requirements

The safety requirements are the agreements that should protect humans and vehicle on the vessel from experiencing any damage. However, this does not imply that complete safety is guaranteed. As IEC states: *The construction of the equipment and operating safety procedures shall provide for the safety of personnel during the establishment of the connection of the ship supply, during all normal operations, in the event of a failure, during disconnection and when not in use. The term safe is not intended to suggest that complete safety is guaranteed, but that risks are minimized*' [48], [49]. The safety requirement have been divided into six categories:

- Electric safety during normal operation.
- Electric safety in the case of failure.
- Mechanical safety during operation.
- Mechanical safety in the case of failure.
- Sufficient testing before installation.
- Sufficient testing, and maintenance if required, during the product lifetime.

The exact requirements corresponding to each category can be found in the List of requirement for appendix B. Notice that these safety requirements are only concerning the actual charging and mooring mechanism. When converting the ferry from hybrid to an electric vessel, of course more modifications are required such as it installation of a shore power station and the implementation of the electric circuit to charge the vessel. For these additional safety requirement are necessary, but this is not in the scope of this research.

Operation reliability

The operation reliability of the mechanism, is an important aspect. The ferry is functioning a part of the Canadian highway system and if it cannot sail, this would result in people not being able to go to work, school or back home. Therefore the charging mechanism should be designed such that occurrence of failures is minimized. Failures include when either the charging mechanism or the mooring mechanism is not able to connect. But is also includes the case in which both systems can connect, but no energy is transferred. Connection failures can be caused by defects in various categories.

- Mechanical construction.
- Material properties of construction.
- charger power system.
- Control system hardware.
- Control system software.
- Alignment deviation.

In appendix B the requirements for each category are presented. These should first of all prevent that connection failures do occur, but these should also ensure that the system is easy to repair once a failure occurs.

Financial requirements

No specific financial limitations are known from BC Ferries. Therefore there have not been set any financial requirements. However one should take into account that the vessel is already sailing in hybrid mode, and BC Ferries themselves decides when they want to convert it into an electric vessel. If this becomes far more expensive compared to the current sailing mode, it is likely that the conversion will be postponed. The costs for the mechanisms can be varying for the investment costs (CAPEX) and the operational costs (OPEX). The CAPEX of a mechanism can be divided in the costs for the mechanism itself and the adjustments to the port infrastructure that is required for the installation. Charging mechanisms for instance can might have a significant weight and a proper foundation for these is than required. The combination of the CAPEX and OPEX form the total cost of ownership.

Since their are no financial limitations provided by BC Ferries, this will only be limited taken into account for the design for the BC Ferries. Basic estimates for the investment and the energy usage are done to argue whether is it a reasonable price that has been set. Extensive cost calculations are out of the scope of this research.

Other operator requirements

The current research for the battery charging options is focused purely on route 18 and route 25, since the two sold ferries will be sailing on this route [27]. However, on the long term BC Ferries wants a total of thirteen ferries to operate also on other routes between thirty ports. BC Ferries requires that the ferries are interchangeable over the routes. This implies that first all, that the plug and socket design should be standardized for each vessel and port. But also the location of the mechanism should be equal on each route, such that the plug and socket are always aligned.

3.4. Determining characteristics

According to the design method from [24], the forth step is to determine the characteristics. This should be done to identify the customers wishes and preferences with respect to the design. Damen has discussed the battery charging options extensively with BC Ferries, but this did not come to a clear vision of what is preferred and what not. The project team from BC Ferries consist of many employees, all working a different department within the company. This results in a situation where each person is mainly focusing on whether a solution is profitable for his or her department, without paying attention to the greater goal. To realize the transition of hybrid to electric propulsion, adjustments to the current situation have to be made in any case. An important characteristic to ease this process might be to limit the amount of changes required to the vessel and port infrastructure and the impact of these.

However, the most significant preference it the reliability of the system. The ferry is operating as a part of the high way infrastructure and when it fails, the consequences are large. This implies that people cannot go to work, to school or back home again. The complete list of preferences is provided in 3.3. In this table, the most important preferences are stated on top of the table. Less significant ones are stated down bellow. In 3.7 these preferences will be used to select the most suitable concept design. Most of these preferences can be traced back form the requirements that have been established in 3.3. In [24] it is suggested that clinics or workshops are done with the customer to gain a better understanding of the specific preferences. Nevertheless, since the customer is located in Vancouver this is not possible within this research.

	Preference
Most important	Operational reliability should be as high as possible.
	Alignment tolerances should be as high as possible.
	Sensitivity to vessel movements should be as low as possible.
	Construction of the system should be as strong as possible.
	Construction of mechanism should be as easy as possible to maintain.
	Mechanical components should be as durable as possible.
	Electric components should be as durable as possible.
	The charging efficiency should be as high as possible.
	Mechanism should be as safe as possible for passengers, crew and environment.
	Electric failures such as short circuit must be unlikely to occur.
	Mechanical failures with respect to the mechanisms construction should be unlikely to occur.
	The implementation of the system should be as easy as possible.
	The required construction work on the vessel to implement the charging and mooring system are minimized.
	The required construction work to the port infrastructure to implement the charging and mooring system are minimized.
	The charging and mooring mechanism should be as generic as possible such that Damen is able to implement this system also for other ferry tenders and other vessel types.
	Total cost of ownership should be as low as possible.
	The investment costs of the system should be as low as possible
	The operational costs should be as low as possible
	Connection time should be as fast as possible.
	Mooring connection is preferably faster than the charging connection.
Less important	Appearance of the mechanism should be professional.

Table 3.3: List op preference for the charging and mooring mechanism for BC Ferries.

3.5. Describe the gap

In section 3.2 the functions of the charging mechanism where discussed. Comparing the requirements for the BC Ferries case from section 3.3 and the state of the art mechanisms found in chapter 2, there is no mechanism which can fulfill all functions within the requirements that were set. In this section is will be identified which functions are specifically hard to realize and from therefore the so called gap. This can be one specific function or, more likely, a specific combination of functions. This section is not an official step in the design method, but this is introduced to get better understanding of which functions should be focused on during the design phase.

First of all, one solution presented in chapter 2 shows to possibility to replace the empty batteries by charged batteries instead of connecting a charger to the vessel. This can definitely be beneficial because the batteries can be charged efficiently by conduction, but the fragile electric connection between the shore and vessel is excluded. Moreover, the time available to charge the batteries is increased, which implies a decrease in energy costs since there is no peak power demand. However, for the BC Ferries case battery replacement does not seems feasible since the batteries are completely enclosed in the vessel as can been seen in figure 3.17. This option will therefore not be taken into account and the case study will only focus on a charging system to charge the vessel battery on board.

Figure 3.17: The location of the batteries in the current design of the vessel for BC Ferries.

Comparing the demands for the BC Ferries case and the state-of-the-art solutions, five requirements are the major causes of why the mechanisms are not suitable for the BC Ferries case.

1. The charging mechanism should be able to compensate a tidal difference of 7.1 m.
2. The charging mechanism may not cause an obstruction for passengers and vehicles moving on and of the vessel.
3. The charging mechanism may not obstruct the port for larger vessels.
4. The charging mechanism should be able to connect when the angle between the ramp centerline and vessel centerline is between -7° and 7°.
5. The mechanism should be able to deal with the expected vessel motions as calculated by a seakeeping calculation.

Requirement number 2 and 3 are not requirements that are function related, but rather construction related. To satisfy these requirements, it is important that the construction of the charging mechanism is designed in such way that is does not cause an obstruction in the water and on the ramp. The other three requirements are function related and these provide the so called gap. Most existing mechanisms do have tidal compensation, but are designed for a smaller height difference. In the Norwegian fjords for instance, the maximum tidal difference is typically 2 to 3 meters [54]. The available systems which do have a sufficient height compensation, are generally shore power systems instead of chargers. These are manual controlled and do not comply with the requirement that the system should be automated. The movement freedom to compensate for misalignments between the ramp and the shore is generally small for automated systems. Especially for the extendible arm concepts, which are used often, the possible deviation in y-direction is only around ± 150mm. Interesting to notice on this aspect, it that all vessels using these chargers have flat rear ends and moor upon the flat shore. This makes an angular deviation between the ramp and vessel unlikely to occur.

The mooring mechanism can than easily be used to secure the vessel in the correct location. This is different from the BC Ferries case, where the vessel has round rear ends and moors in a funnel shape between the wind walls. It is important that these angular misalignments are taken into account for the new design. Lastly, the flexibility of the existing mechanisms is generally smaller than demanded for the BC Ferries case. Most electric vessels that are currently operating are sailing in fjords, where waves are typically lower compared to the relative open water where the BC Ferries are sailing. It can therefore be argued that the vessel motions are smaller and therefore the required flexibility is less. However, the main reason for operational failures of the mechanisms charging these vessels, are caused by a lack of flexibility. Summarizing, most existing charging mechanisms are designed to provide flexibility to only small vessel motions and fall short to do so. It is therefore of major important that the flexibility of the new design is well calculated and verified.

In the following part of this chapter a new charging mechanism will be designed, with the focus to find a solution for the following three functions:

- Compensate the tidal difference.
- Provide flexibility.
- Deal with misalignments.

3.6. Generating alternatives

For the generation of a new charging and mooring mechanism, first a morphological overview is set up. This is provided and explained in 3.6.1. The sub-solutions devised here are used to design multiple mechanisms that could provide a solution in 3.6.2. These will be evaluated on a basic level, after which 3 concepts are chosen to elaborate on. These mechanisms will be work out in some more detail and this design will be described in 3.6.3.

3.6.1. Morphological Overview

For the functions of the charging mechanism, a morphological overview was created. This is shown in figure 3.18. This overview purely focuses on finding sub-solutions for the functions that where identified as the gap. These functions are not well developed yet and require additional research. The other functions are established technologies and are expected to be implemented relatively easy in the the system. Furthermore, conduction and induction are given as the possible power transfer technologies since it was already determined in chapter 2 that the other technologies researched are not desired. Note that the solutions provided in the morphological overview are not required to be actually feasible. However, these out-of-box solutions can help to extend the view of possibilities. The feasibility of the solutions will be discussed in the following subsections.

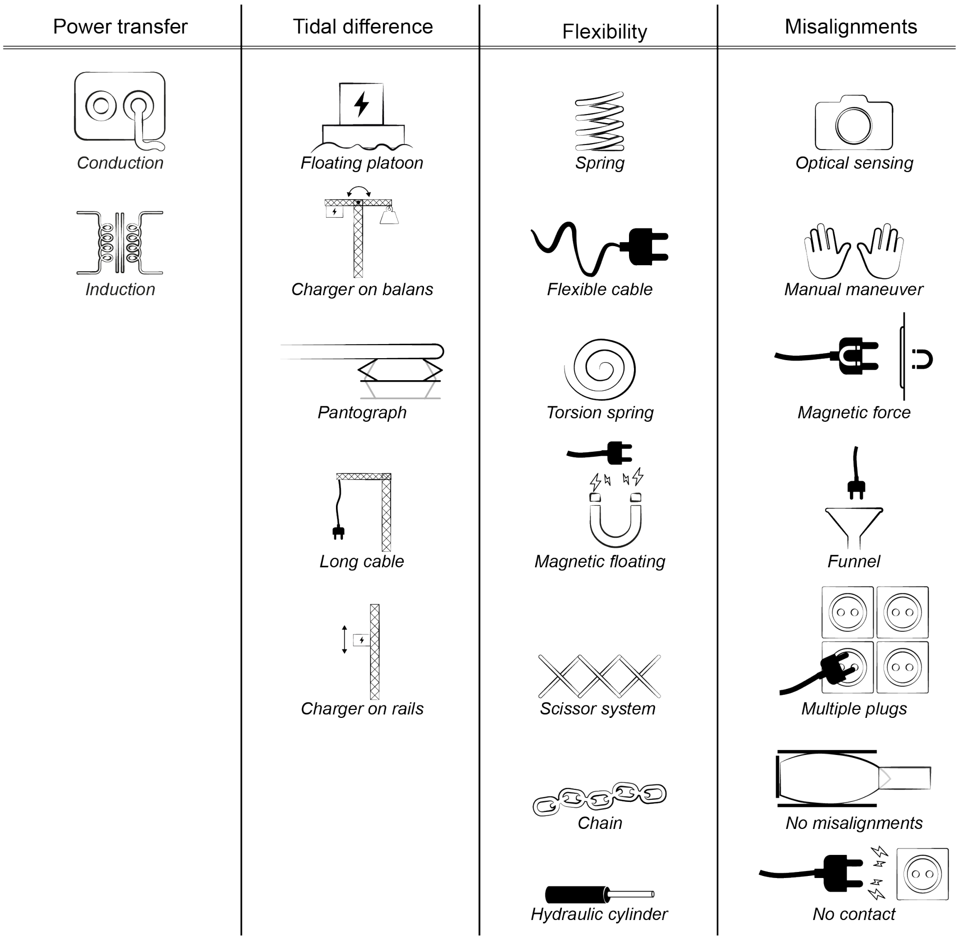


Figure 3.18: The morphological overview of the charging mechanism, covering the critical functions as found in the identified gap.

3.6.2. Brainstorm

The different sub-solutions of the morphological overview were combined in various ways to create concepts for a charging mechanism. The brainstorm should be open minded and non-feasible ideas can be written down as well. This ensures that no concepts are rejected while they could have some potential and it helps the designer to stay open minded. An impression of this brainstorm, is given in figure 3.19 but is not discussed here in more detail. Following, the concepts that look most promising are selected. These will then further discussed in section 3.7.

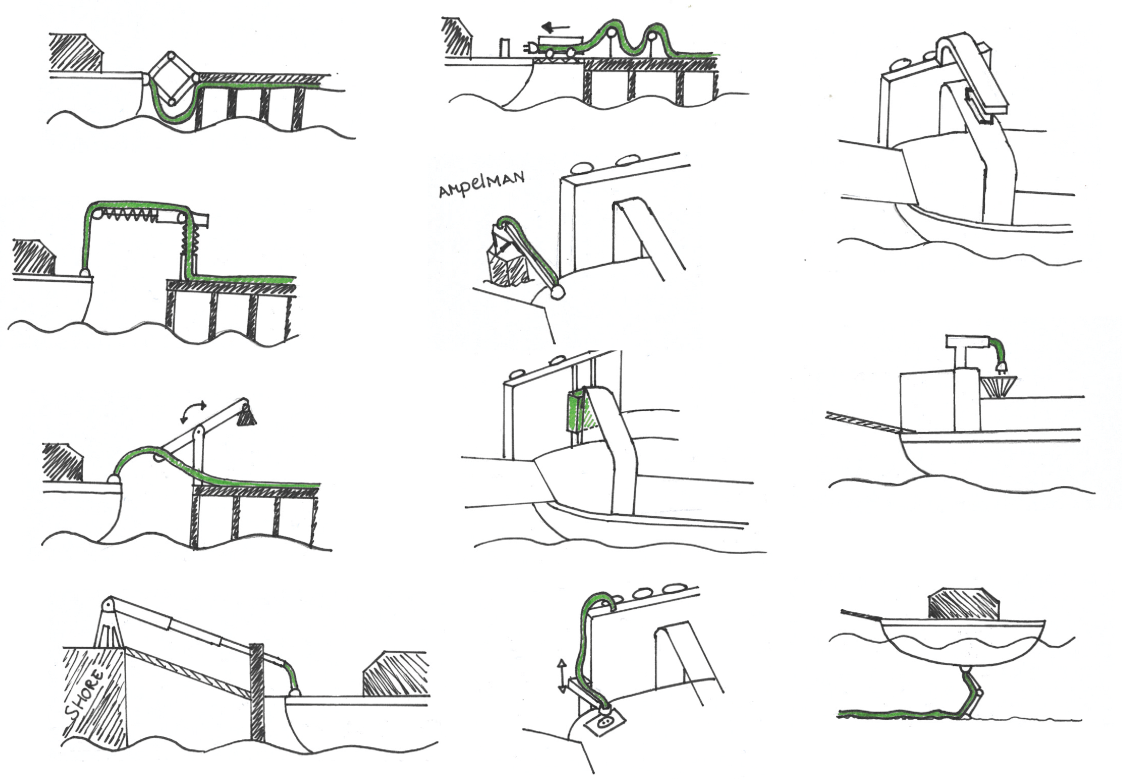


Figure 3.19: An impression of the concepts developed during the brainstorm for a charging mechanism.

3.6.3. Final concepts

For a new charging mechanisms, three systems that seems most promising have been chosen to further think through. This decision was based on several criteria, related to the gap that was identified in the previous section. These criteria are:

- Charger location in the port.
- Charger location on the vessel.
- Expected charger performance → flexibility.

As mentioned in section 3.5, the construction of the mechanism should be such that it does cause an obstruction for other vessels of for passengers and vehicles. Furthermore, the design should of course be able to fulfill all functions defined as the gap. However, since the most failures of the existing mechanisms occur due to a lack of flexibility, this part is emphasized while making a selection of the concepts. Concerning the space that is occupied by the mechanism, most existing mechanisms are either placed next to the ferry, where it obstructing the port for other vessels, or on the ramp to the shore, where it is blocks the road for vehicle and passengers moving on and off the ferry. The typical layout of the BC Ferries ports is analyzed as shown in figure 3.20. The ramp is excluded as a potential location because this is too narrow to let traffic pass next to a charging installation. Furthermore, it is doubted whether the ramp would be sufficiently strong to carry the required loads if there was enough space available. Also the space alongside and behind the ferry is rejected, since this must remain free for larger vessels as already discussed before. Last, the dolphins are unsuitable for the installation of a charging mechanism as well. It is uncertain if the foundation of these is capable of supporting a charging installation, but their location is also varying for each port. This would make it not possible to produce one standardized design, suitable for all ports.

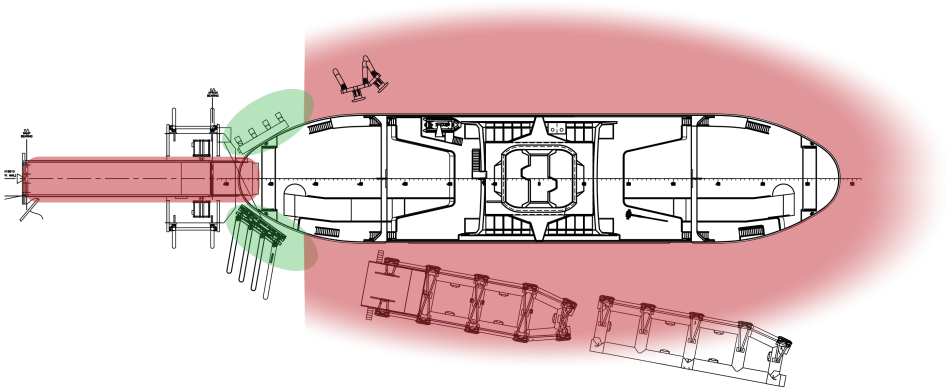


Figure 3.20: The locations in the port where a charger could be located, indicated by green, without causing an obstruction for other vessels or traffic on the ferry.

Also for the installation on the vessel, the main restriction is that it may not obstruct the vessel for passengers and vehicles that are willing to go on or of the ferry. Furthermore, the installation may not decrease the available parking spots on the the ferry. Figure 3.21 gives an impression of where the mechanism can possibly be installed. The area where the traffic is running, is of course rejected as a possible location. This leaves at the front of the vessel only the two corners. Other possible locations that could be utilized for the installation of a charging mechanism are on the side of the vessel and the spoiler that the mounted on both ends of the vessel.

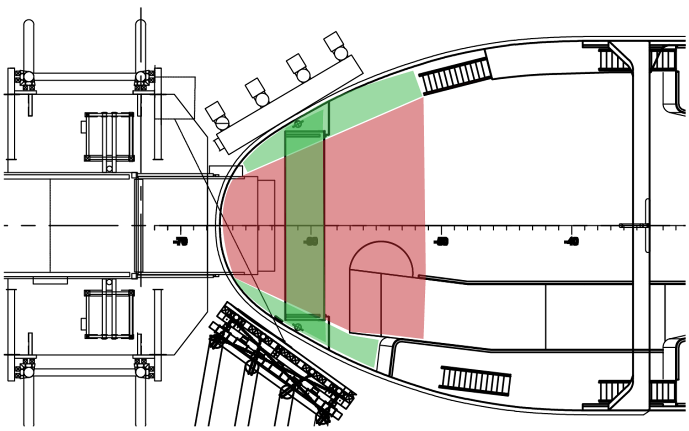


Figure 3.21: The locations on the vessel where a charger could be located, indicated by green, without causing an obstruction for traffic on the ferry on protect it from passengers as much as possible.

The reliability of the current existing mechanisms is in general lower than desired. The main cause of this issue, is the lack of flexibility. Although the exact flexibility is not known for the concepts during the brainstorm, an estimation of the expected flexibility can be made. First all, the wireless concepts are expected to be relatively flexible since there is not physical connection between the ship and the shore. For the conductive concepts, it is expected that the largest flexibility is obtained with a vertical connection between the plug and the socket. By connecting the plug and cable vertical to the socket, the gravitation force of these components is aligned with the socket orientation. Therefore the expected torsional force in the plug-socket connection is less compared to a horizontal connection for the same vessel motions. This is important since torsional forces cause easily disconnections and damages in the plug-socket connection. A vertical connection is therefore expected to bear a larger freedom of motions.

Based on these criteria, three concepts have been chosen which will be further investigated in 3.7. These concepts, and the sub-solutions that were combined to form the concept, are shown in figure 3.22. The first concept shows a crane like mechanism which connected to the wind wall. Once the ferry is docked, the plug in moved downwards into the socket. The structure is long enough to compensate for the maximum tidal difference of 7.1m. The beam connecting the plug to the wind wall will incorporate some spring suspensions to provide flexibility to the vessel movements during charging. The second concept shows a pantograph solution. Also for this concept, the connection between the plug and the socket is vertical to provide more flexibility. The pantograph for other vehicles such as train and electric buses is already a proven technology when it comes to both transfer of electricity and providing flexibility. The nice thing about the pantograph would also be that the connection is easily protected from vehicle and passengers due to its height. The pantograph construction should be mounted to a certain structure on which it can move vertically to compensate for the tidal difference. The last concept shown is a variant of the inductive charging of Wärtsilä. The dimensions have been adopted from the Wärtsilä concept and so is the level of power transfer. Since one coil can only transfer 2.5MW, two of these should be installed to provide enough charging power. For this concept the coils have are mounted in the wind wall, such that it can move up and down to compensate for the tidal difference and that is does not obstruct the port any more for other vessels. By mounting the ship coils into the side of the vessel, the interaction with persons and vehicles on the vessel is limited.

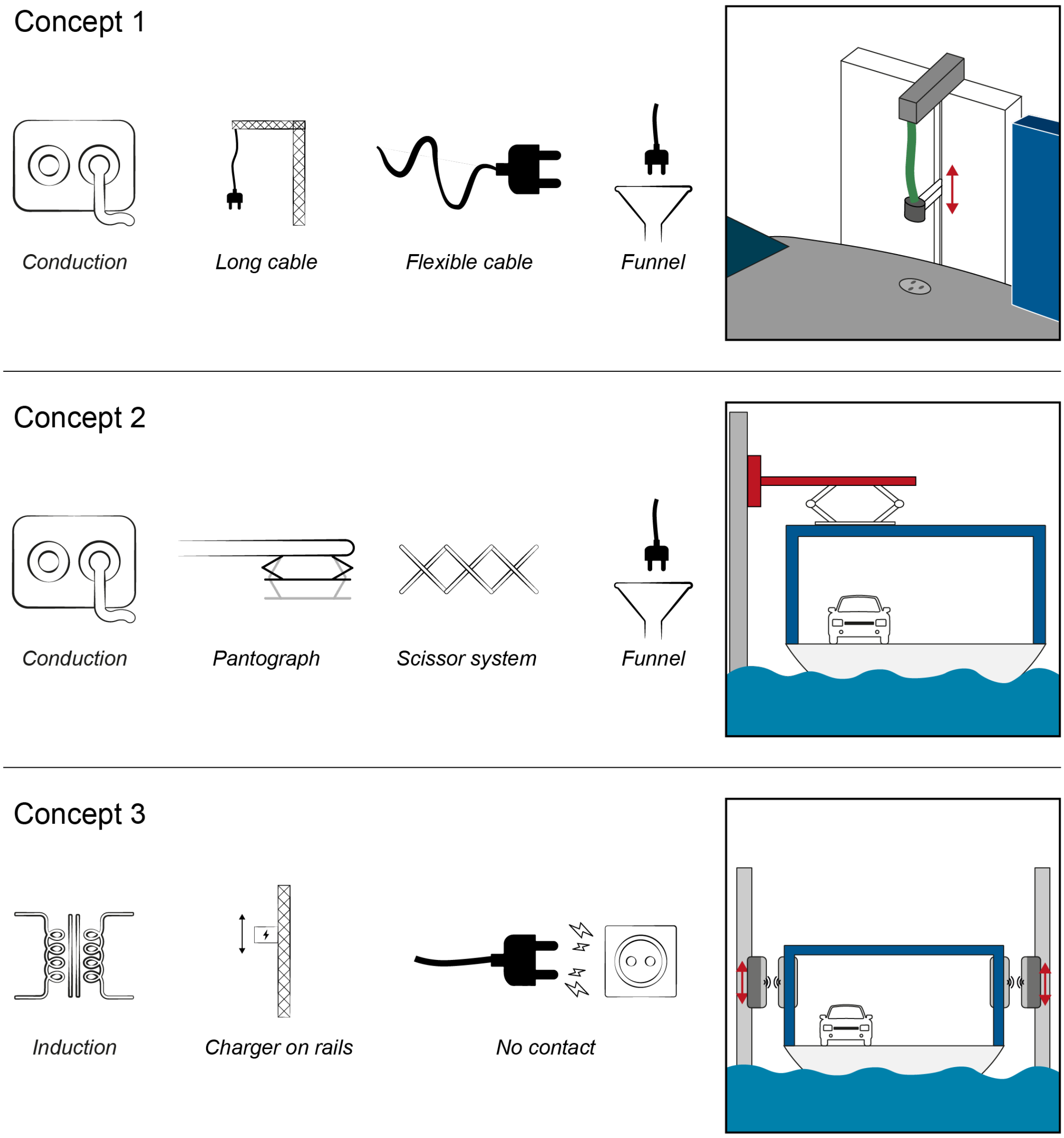


Figure 3.22: The three concepts that have been chosen to further elaborate on, created from the sub solutions define in the morphological overview.

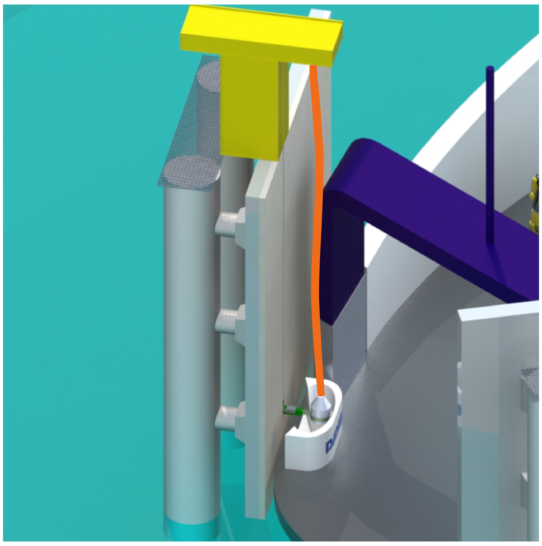
3.7. Evaluating alternatives

This section elaborates on the concepts that were presented in the previous section. In 3.7.1 more details of the design are determined in order to be suitable for the BC Ferries case. The designs developed here, will be evaluated in section 3.7.2 where they will be tested against the preferences determined 3.4. A Harris profile is used to score each concept for all preferences. The outcome of this Harris profile will indicate the most suitable charging mechanism for the BC Ferries case.

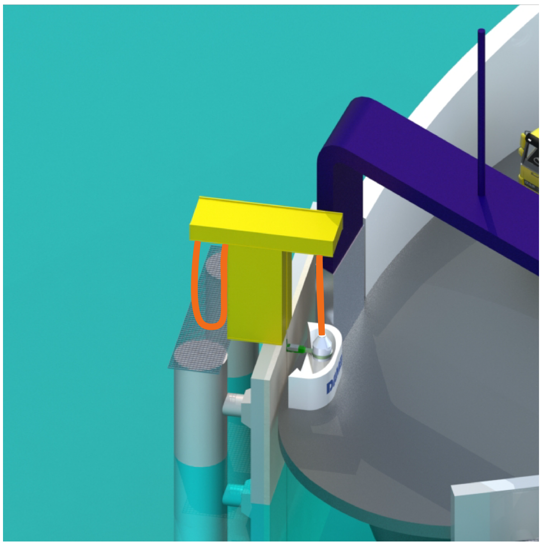
3.7.1. Design details

The concepts form section 3.6 are described below to some further extend. In the designs cables are depicted to show the cable configuration that is imagined. In the concepts this is shown as one think cable, but in the final design this will possibly be a collection of multiple cables. The exact amount of cables and the cable dimensions will only be determined for the final chosen design in the section 3.8. For the configuration of the cables in the charger design, it has been taken into account that the cable flexibility is limited and that the bending radius is large.

Concept 1, Vertical plug



(a) The configuration of concept 1 for the lowest water scenario.



(b) The configuration of concept 1 for the highest water scenario.

Figure 3.23: The design of concept 1 for the extreme values of the water level.

Figure 3.23 shows the final design of concept 1. In figure 3.23b the configuration for high water is shown and figure 3.23a shows the situation for the low water scenario. This concept is based on a general crane mechanism. However, the plug is connected to a beam that is again connected to the wind wall. This prevents the plug from swing and it enables to move the plug vertically without putting pressure on the sides of the cable. The cable in always aligned vertically above the plug, whereby the forces of the cable on the plug are minimized. Once the vessel arrives, the plug is moved downwards by the green beam until it reaches the socket. The beam is locked when it is not in operation, but can be unlocked by opening the flap as shown in figure 3.24. This green beam consists of multiple parts connected to each other by both linear and torsional springs. This can be seen in figure 3.24 Do to the funnel shape of the socket, the springs will deform and the plug is guided in the correct position in the case that the plug and socket are not well aligned. This way, the beam is only controlled in vertical direction and the misalignment correction is a passive system. The plug is secured into the socket while charging. Once the vessel is ready to depart, the socket releases the plug again and it is pulled out by the green beam. A consequence of the funnel shape of the socket, is the risk for water ingress from rain of spray water. A protective system, for example a shutter, should be implemented to prevent this to occur.

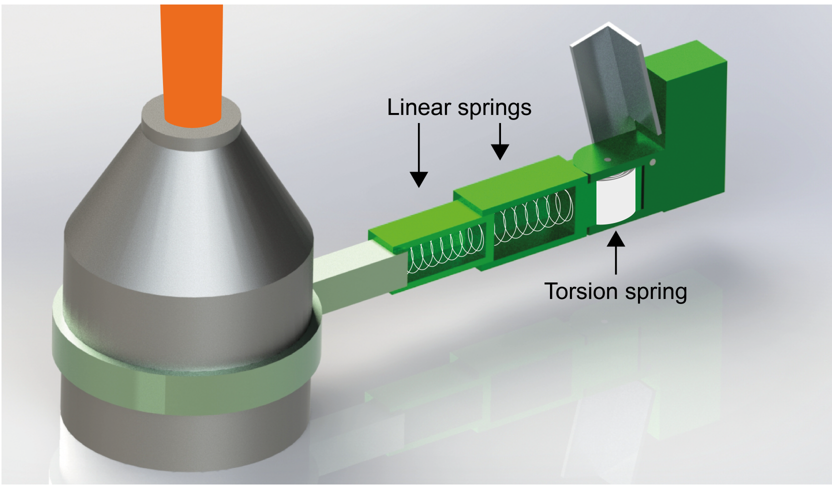
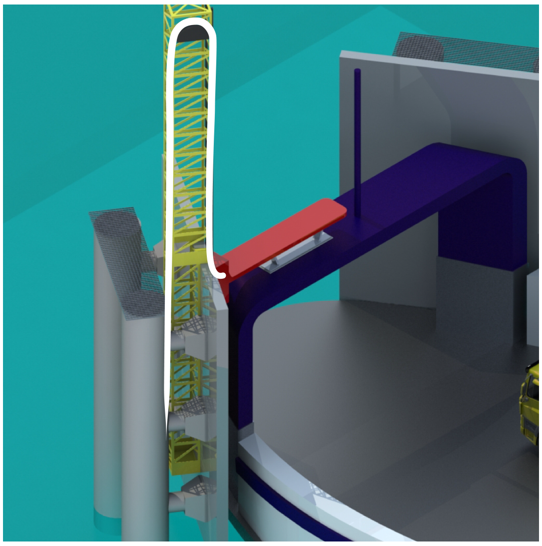


Figure 3.24: The springs incorporated in the beam such that funnel shape of the socket can correct the plug position to ensure that the socket and plug are correctly aligned.

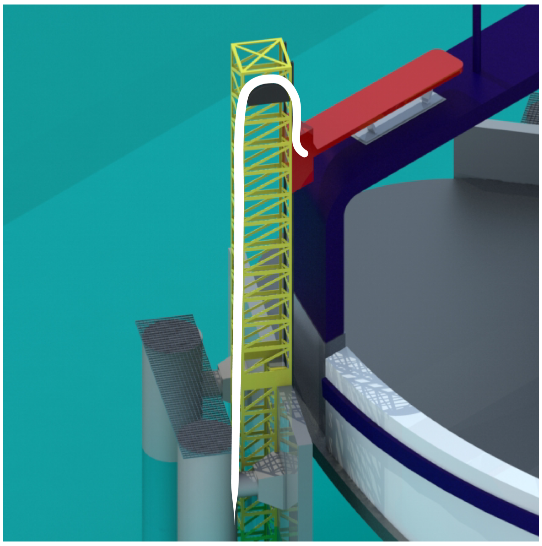
To be able to compensate for the tidal difference, the crane should extended ca. 3 m above the wind wall. This ensures that the cable has still a significant length in the case of extreme high water, which decreases the cable stiffness. Based on the weight known for various existing charging mechanisms, the expected weight of the shore side installation is ca. 10,000 kg. The ship side installation is expected to be ca 1000 kg. For the installation of the system, modifications to one wind wall are required. From the charger perspective, it is possible to mount the system on the wind wall structure. However, it should be investigated if the wind wall foundation is able to support the additional weight.

The investment costs for one system are estimated around €1,000,000, based on the investment costs of the existing mechanisms discussed in chapter 2. Since the mechanism is charging by conduction, the charging efficiency will be high. Additional aspects that are out of the scope of this research will influence the total costs of the system significantly, such as the use of a shore battery. The connection time is estimated to be ca 30 sec. By including current water level in the control system of the shore installation, the plug can already adjust its height before the vessel arrives in the port. Once the ferry arrives, only a small vertical distance should be traveled by the plug, approximately 2m, which minimizes the connection time.
The reliability of this system is expected to be good with respect to a horizontal plug connection. Due to the vertical connection, the occurrence and magnitude of torsional forces in plug-socket connection is expected to be less. This is one of the main causes that plugs get disconnected from the socket. Furthermore, due to the vertical alignment and the passive misalignment correction, connection depends only on the vertical displacement from the beam connected to the wind wall and not on optical sensors. Therefore it is less sensitive to external disturbances.

Concept 2, Pantograph
Figure 3.25 shows the final design of concept 2. In figure 3.25b the configuration for high water is shown and figure 3.25a shows the situation for the low water scenario. This pantograph design is working different compared to the pantographs used for trains. For trains, the positive pole is located on top of the train. The negative pole of is created by the rails. The train pantograph can therefore touch the overhead wire relatively arbitrary. For this concept, the pantograph is rather comparable to the ones used to charge electric buses [5]. This can be seen as a large overhead plug which connects to both the positive and the negative pole of the vehicle. Due to the height of the spoiler, on top of the varying water height, the system should extend ca. 9m above the wind wall. The weight of the ship side installation is expected the be relatively small, since there is not an actual installation required. The additional weight only comes from the socket that is mounted in the spoiler, and the cables running through the spoiler connecting the socket to the onboard grid. The estimated weight of the shore side system 20,000 kg, based on the weight of other tower solutions that were found in chapter 2. It should be investigated whether this can be mounted on the wind wall foundation or that it requires a separate foundation to support the additional weight. For the conversion from hybrid operation to



(a) The configuration of concept 2 for the lowest water scenario.



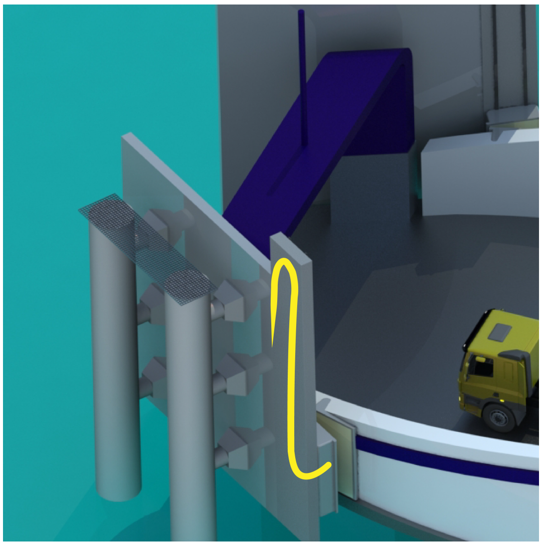
(b) The configuration of concept 2 for the highest water scenario.

Figure 3.25: The design of concept 2 for the extreme values of the water level.

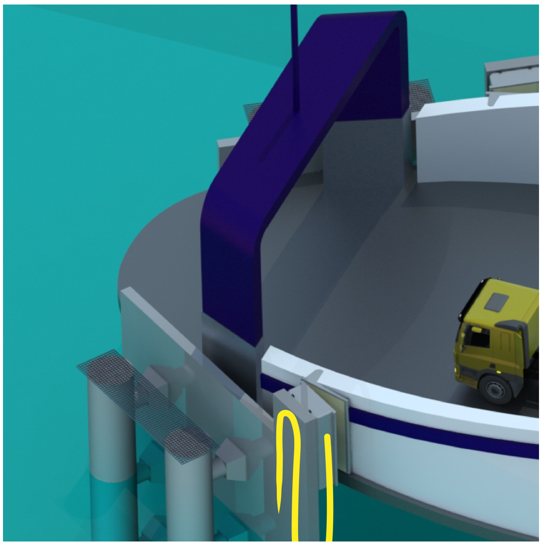
full electric sailing with concept 2, the spoilers on the vessel should probably be replaced by reinforced spoilers which are designed to carry the cable load and the forces exerted on it from the pantograph. In the ports, construction work should be carried out at one wind walls and, as stated before, possibly a foundation for the system should be placed in the water.
Flexibility in the z-direction is provided by the pantograph which deforms with the movements of the vessel. Because the pantograph includes both the positive and the negative pole, the alignment between the vessel and the pantograph is crucial for a good connection. Such, the flexibility in the xy-plane is expected to be relatively small. For this system to work it is essential that the captain docks perpendicular to the shore and that the mooring mechanism is able to limited the surge, sway and yaw motions. The investment costs for one charging system are estimated around €750,000. Based on the known investment costs of existing mechanisms form chapter 2. The energy costs will be comparable to the costs of concept 1 since both are charging by conduction and the charging efficiency is expected to be comparable. The expected connection time is 15-30 sec, which is some faster than concept 1. This is since the pantograph is only required to move in one direction. When the current water level is included in the control system of the pantograph, the height of the pantograph could already be adjusted to the correct level before the vessel arrives. Once it does arrive, the vertical distance that the pantograph should still move is minimized and so is the connection time. The system reliability is expected to be some less compared to concept 1. Although the pantograph is a simpler design, and has therefore less components that might fail, the lack of flexibility in the xy-plane is expected to give issues in certain situations. This includes for instance cases where heavy side wind or current is experienced. In the case that this concept is selected as the best option it is important that this aspect is further investigated. The convenient parts about the pantograph design, is that the charging occurs high above the passengers and vehicles. Interaction between the charging system and humans is therefore excluded. Also due to the automated control of the system, no operator is required to come near to the charging system.

Concept 3, Inductive charging

Figure 3.26 shows the final design of concept 3. In figure 3.26b the configuration for high water is shown and figure 3.26a shows the situation for the low water scenario. The global dimensions of the mechanism have been adopted from the Wärtsilä wireless charging system. Since this is a more or less proven system, it seems reasonable to collaborate with this supplier in this case that this concept is chosen. But and even if there will be no collaboration with Wärtsilä, the dimension of the new design will be probably in the same range since the coil size is determining for the level of power transfer. The expected weight of the coil is ca. 2500 kg, also based on the Wärtsilä design. Besides, both coils should be insulated by an aluminum plate to protect the surroundings from the induction around the coil. Therefore the total weight of the ship side installation including the insulation and additional cabling is estimated to be 3000 kg per side. Furthermore, the coil on



(a) The configuration of concept 3 for the lowest water scenario.



(b) The configuration of concept 3 for the highest water scenario.

Figure 3.26: The design of concept 3 for the extreme values of the water level.

the shore side should be mounted on a structure to move it up and down. The shore side installation will be around 12,000 kg per side. This includes the frame, the drive line to provide the vertical displacement and the required cables. However, the system should be build next to the wind walls, since the coil dimensions do not allow the system to be mounted on the wind walls. The system requires therefore an additional foundation in the water, next to the wind wall. The modifications to both the vessel and the port design are intensive compared to the first two concepts. This has mainly to do with the fact that the coils should be mounted on both sides of the vessel in order to acquire the desires power transfer. This means that both wind walls and their foundation should be renovated, while these are already standardized for all BC Ferry ports. On the vessel side a total of four coils have to be mounted into the vessel side. Since the plate thickness of this wall is not designed to carry such a load, while there is a hole in the wall of $5m^2$, it is reasonable to believe that the vessel wall should be reinforced and adjusted to fit the coil dimensions.

The flexibility of the system is expected to be relatively good for small motions of the vessel since inductive charging is wireless. However, the space between the coils is limited due to the port and vessel layout, as can be seen in figure 3.27. Therefore, the movements in y-direction are limited ± 210 mm before the coils touch each other which might cause damages. Of course a safety factor should be included for the flexibility, which decreases the freedom of the movement in y-direction even further. Flexibility in x-direction does not seem an issue, since it the vessel cannot move further forwards do to the wind walls and backwards movement cannot cause any damage. The system is relatively flexible in z-direction, but the charging efficiency decreases with an decreasing overlap area.

The investment costs of one Wärtsilä are ca. €1,500,000. Since this concept requires basically two of these systems, the investment costs are estimated to be €3,000,000. The energy costs of this concept are expected to be higher compared to the other concepts. Since inductive charging is less efficient than conductive charging, more power will be lost during charging.

The expected connection time is faster compared to the other two concepts. Because no physical contact has to be realized for charging, charging can start as soon as both plates are sufficiently overlapping. Therefore charging will already start before the vessel is moored. The same applies to the vessel departure, the vessel can be unmoored and continue charging until it actually leaves and the overlap area drops below certain level.

Most reliability issues of the currently existing mechanisms occur either when making a connection between the plug and the socket, or when they are already connected but too sensitive the vessel motions. Since inductive charging does not have to deal with these issues, the reliability is expected to be relatively high. However,

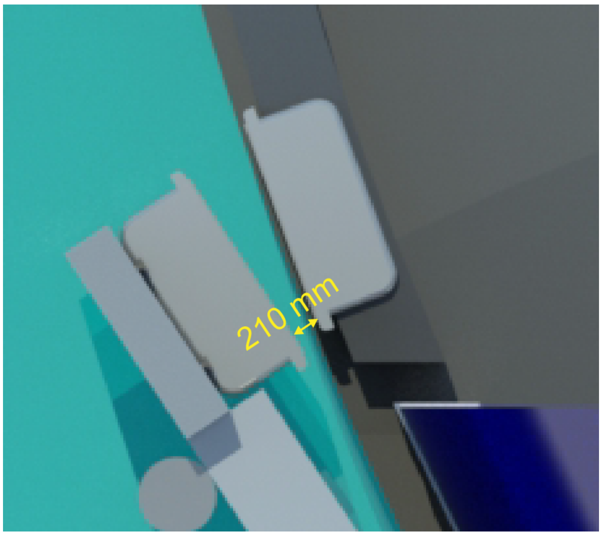


Figure 3.27: The distance between the shore and ship coil, in the case that the distance on the left and right side of the vessel is equal.

when the overlap area decrease, so does the charging efficiency. This is expected to occur regularly, due to waves which make the ship side coil move in all directions but mainly in vertical direction. The reliability for charging in general will be relatively high, but for charging at maximum efficiency will be low compared to the other concepts.

To protect the passengers and vehicles from the induction created around the coils, aluminum plates are inserted. Since the power transfer occurs on the outside of the vessel, interaction with passengers is minimized. The coil is mounted on the edges of the vessel and therefore the system will not obstruct the passengers. However, due to the significant dimensions of the coil some spaces might become narrow. Since there is not physical human interaction is required for connection or so, these safety risks are excluded. Because the charging occur wireless, galvanic isolation is ensured. Another advantage of wireless charging is that the system will not get damaged in the event that the vessel departs without decoupling the charger.

3.7.2. Concept selection

For selecting one concept, the preferences from section 3.4 are used to investigate which concept is most desirable for the BC Ferries case. The design methodology from [24] prescribes to use the weight objectives method for the selection process. This is a relatively detailed method in which all preferences are valued from 1 to 10. The next step is to ascribe a score to each preference for each concept, again on a scale of 1 to 10. Since the ranking of this method is quite detailed, one should be able to clearly reason the decisions. For instance why a concept scored a seven, and not a six or an eight. Since the concepts for the charging mechanism are rather global defined, this method does not seem the appropriate. Therefore, there is chosen to use a Harris profile as a selection method instead. For a Harris profile the preferences are not ranked by a specific value, but they are just sorted from top to bottom with the most important preferences at the top. The concepts do not get a specific score for each preference, but only green or red boxes. Green boxes indicate that this preference is relatively well satisfied compared to the other concepts, red boxes indicate that is it worse with respect to the other concepts. It should be assumed that a concept is always good or bad with respect to the others, so combining red and green boxes is not allowed. A concept can score either one or two boxes to show how large the difference is between some concepts. The Harris profile for the three charging mechanism concepts is shown in figure 3.28. The order of the preferences in figure is equal to the order that was already established in section 3.4, where the most important requirements are stated at the top and the least important at the bottom. Additional motivation on the judgment of the concepts is provided below.

Reliability
Concept 1 scores better compared to the other concepts because of flexibility and charging efficiency. Concept 2 comes with a large freedom of movement in vertical direction, but is it expected to be more sensitive to vessel motions and misaligments in the horizontal plane. The other concepts have a larger freedom of

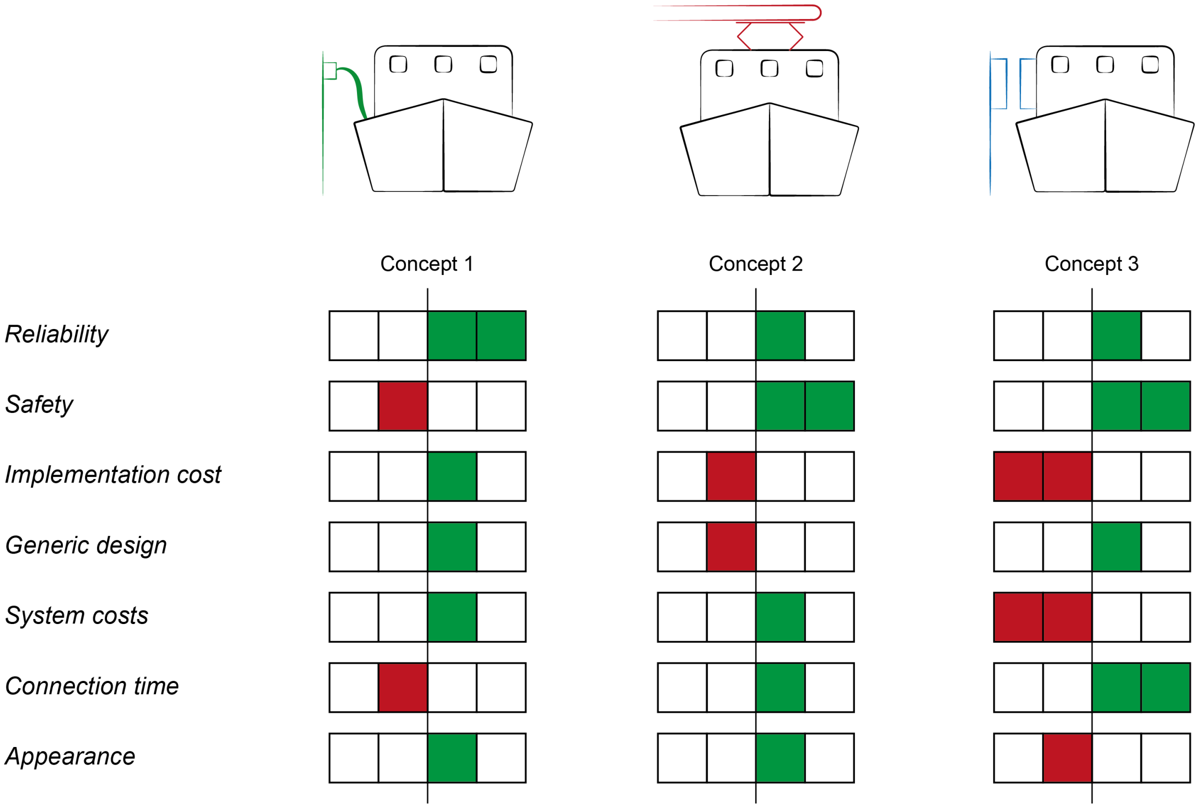


Figure 3.28: The Harris profiles for all concepts, scoring them on the preferences from section 3.4.

movement and are therefore expected to be more reliable due to flexibility and the ability to deal with misalignments. Concept 3 however, will come with a lower charging efficiency compared to the other concepts since it is transferring the electric energy by induction. Therefore the system is expected to be less reliable to transfer the desired energy in the restricted amount of time.

Safety
Concept 1 scores worse on safety compared to the other concepts, due to the possible interaction with passengers and vehicles. Concept 2 and 3 are protected from this interaction because they are placed over the traffic or on the outside of the vessel respectively. By excluding possible contact between passengers and the charging mechanism, safety risks are minimized. For concept 1 the onboard connector is placed on the deck where passengers and vehicles are moving. A suitable location and construction of the connector should be taught through to minimize the chance of dangerous situations.

Implementation costs
The relative implementation costs are estimated based on the number of modifications required to the port infrastructure for the installation of the system. Concept 3 scores worst compared to the other concepts since the charging system should installed on both sides of the vessel. To do so, both wind walls in the port should be modified, while for the other concepts only one wind wall has to be adapted to the charging mechanism. Since the pantograph from concept 2 is reaching further from the wind wall and requires a higher vertical displacement compared to concept 1, it is expected that the realization of concept 2 requires more modifications to the wind structure to support the charging system. Therefore concept 1 scores best out of the three constructions. No concept is given two green blocks since the wind wall should be modified in any case, which is not desired.

Generic design
The desire to have a generic design is not something that is preferred by BC Ferries, but this is desired by Damen to use the design for other vessel as well. Concept 2 scores worse compared to the other concepts, since the design is only applicable to vessels with an onboard spoiler. Other two concepts score both one

green box since these are more generic compared to concept 2, but have their limitations as well. Concept 3 comes for example with relatively large dimensions of the onboard system and it therefore not expected to be suitable for relatively small vessels. For concept 1 the socket is required to be installed near to the vessel side which might be undesired for certain vessels.

System costs
The exact investment costs is not known, but an estimate could be done based on the known values of the costs of already existing systems. For concept 3 this is around 3 million euros, while the other systems are both expected to be approximately 1 million euros. Furthermore one should take into account that the charging system should be installed on all ports on ferry route.

Connection time
Concept 3 scores best on connection time since this system does not require a physical connection and can therefore start charging already before the vessel is actually moored. Concept 1 and 2 but require vertical displacement. Next to this, concept 1 also requires to maneuver the plug in the horizontal plane. Therefore the connection time for concept 1 is expect to be longer compared to the one for concept 2.

Appearance
Due to the large dimensions of the inductive charging units, is it hard to integrate this nicely into the current infrastructure. The boxes on the wind wall, will possibly look rather strange and not very professional. The other concepts can possibly be more smoothly integrated into the wind wall, might provide the system a more professional appearance. However, the final design of the concept is playing a large role in this result and not so much the physical principal of the system.

Based on the evaluation form the Harris Profile, concept 3 has been rejected. This decision is mainly base on financial reasons. The implementation of this concept in the port is expected to be more expensive compared to the others, since two systems should be installed and therefore both wind wall should be reconstructed. Also the investment costs of the system itself is expected to be significantly higher compared to the other systems and are even approximately half of the investment costs of the entire vessel. Furthermore, also the energy costs of this system will be higher than for the other two concepts due to the lower energy transfer efficiency of induction compared to conduction. The difference between concept 1 and 2 however, is not that significant. Both systems have difference advantages and disadvantages, but their overall score is comparable. Due to the limited time available for this research only one concept will be chosen to work out into more detail, which will be concept 1. The main reason for this decision is the fact that various crane concepts for the charging of electric vessels does already exist, such as the ones from figure 2.6a, 2.5a and 2.5b. Concept 1 is basically a variation of these concepts. A pantograph system has not yet been developed for vessel charging. Therefore, the detailed development of the entire pantograph system such as concept 2 will probably require a lot more time compared to concept 1. In the following section the design details for concept 1 will be determined and explained. These details will many focus on the cable selection and their alignment in the mechanism. Since the cable selection is important for the flexibility of the system and the coverage of the tidal difference, which covers the defined gap from section 3.5. Other aspects from the mechanism, such are the crane structure or the control system, are likely to be adopted from existing systems.

3.8. Improving details

To recap the gap defined before, this included the combination of three functions. Besides, the location of where the system will be installed was found to be critical. The charger may not obstruct the port for larger vessels and may not obstruct the ramp for traffic moving on and of the ferry. This has been dealt with by installing the system on the wind wall. The critical functions included that the tidal difference should be compensated by the system, it should deal with misalignments between the vessel and the port and system should be sufficiently flexibility to handle the vessel motions. The alignment deviations are handled by the funnel shape of the socket which corrects the position of the plug in the case that the plug and socket are not properly aligned. The tidal difference compensation is tackled by the crane like construction.

The flexibility of the charging mechanism should be provided by the flexibility of the power cable. However it was already seen in chapter 2 that the power cable mechanics have been an issue for various mechanisms. This included for example a lack of flexibility of the cable causing the plug to disconnect form the socket and another system where the power cable was deformed due to continuous cable maneuvering. Therefore it was decided to execute a FEM calculation on multiple cable configurations, and this way, select a power cable which shows to be suitable for this case study. This is described in subsection 3.8.1. The outcome of this simulation will be implemented in the final design, which is presented in 3.8.2

3.8.1. Cable simulation

The cable simulation is set up to predict the behavior of various cables as a consequence of the vessel motions. First the set up of the model is described. Subsequently the output of the simulation is given and progressed to use the results to determine the most suitable cable. Afterwards, the simulation is evaluated. Here the reliability of the results is discussed and possible improvements for future simulations are mentioned.

Simulation setup

The model used in the simulation is shown in figure 3.29. The type of cable and the amount of cables is varied for the simulation. Three different cable configurations have been selected to consider which are shown in table 3.4. The first two configurations concern cables for the LV scenario, with on one hand fourteen thin and relatively flexible cables and on the other hand four thicker and stiffer cables. Furthermore, one HV cable is studied. This study is supposed to provide clear insight in the cable behavior when it is exposed to the motions of the vessel, such that a well substantiated decisions for a certain cable configuration can be done. Notice that the bending radius for these cable is described as the smallest radius to which the cable can be bend without getting damaged. This does not state anything on its flexibility or the effects of continuous deformations.

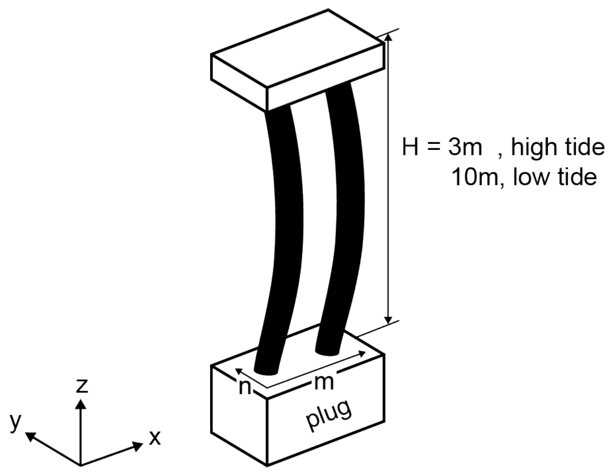


Figure 3.29: The set up of the model used for the FEM simulation of the cable behavior.

Configuration	**Voltage**	**Core CSA** $[mm^2]$	**# Cores**	**Weight** [kg/m]	n x m	**Bending radius** [mm]
1	LV	185	1	1.920	2 x 7	265
2	LV	240	4	10.690	1 x 4	680
3	HV	150	3	9.040	1 x 1	567

Table 3.4: The cable configurations that will be tested in the FEM simulation.

The cable layout of the LV cables was adopted from the H-Flex PWR C-Pur cables from Helkema Bica. For the HV cable, the MPRXCX ® FLEXISHIP® from Nexans is used. Both contain a stranded copper core from class 5, which indicates that is a cable designed for flexible use [46]. The material properties of all layers within the cable have been converted into one homogeneous cable material to decrease the necessary calculation time. The cable configurations are exposed to two motions patterns given in equation 3.1 and 3.2. These are based on the vessel motions that where calculated by the sea keeping simulation in 3.3.1. Motion pattern

1 presents the worst case scenario for movement in the y- and z-direction. However, the movements in x-direction are negligible for this scenario. Therefore motion pattern 2 is analyzed as well, presenting the worst case scenario for movements in the x-direction. All cable configurations are tested for a cable length of 3m and 10m, presenting the case for the highest and lowest water level respectively. So twelve calculations have been executed in total.

$$\begin{aligned} d_x &= 0 \\ d_y &= 0.086 * \sin(1.24 * t) \\ d_z &= 0.27 * \sin(1.24 * t) \end{aligned} \tag{3.1}$$

$$\begin{aligned} d_x &= 0.015 * \sin(1.24 * t) \\ d_y &= 0.078 * \sin(1.24 * t) \\ d_z &= 0.085 * \sin(1.24 * t) \end{aligned} \tag{3.2}$$

The calculation time for the simulation can be significant for non-linear problem, which this is. Assumptions have been done to simplify the FEM model and such limit the calculation time. The assumptions done are:

- The top of the cable is fixed.
- The entire plug is moved with the prescribed displacement of the motion patterns described in equation 3.1 and 3.2, such that the plug is not rotated.
- The cables are modelled as solid homogeneous cables. The material properties of these homogeneous materials have been calculated based on the limitations given by the cable supplier. To do so, the minimum bending radius and tension limit in the copper parts are combined to calculate the elastic modulus.
- The cables are slightly buckled when the plug is at it lowest position.
- Only one periodic movement of the cable is simulated to keep the calculation time limited.
- F_z does not include gravitational forces, but only added vertical forces do the to the plug displacement.
- Only gravitational forces of the cable itself are effect the cable movement, not the other components.
- The material properties used for the cable material are at room temperature (20°).

The simulation is executed to check whether the system is expected to fail or get damaged for a certain configuration, since was observed for currently existing mechanisms in chapter 2. The demanded outputs of these simulation are therefore

1. The maximum tensile stress within the cable. When the tensile stress in the cable exceeds a specified limit of the material properties, cable deformation or fractions might occur.
2. The resultant forces of the plug. These cause forces between the plug and the socket, which can cause damages to the plug pins.

Simulation results

The output of all calculations as a function of time can be found in appendix D. The highest stresses and forces that the output gives for each situation are provided in an overview in table 3.5. The given forces are measured on the plug, at the connection point of the cable and the plug as shown in figure 3.30. This was chosen for modelling purposes. However, when reading the table, one should notice two important aspects:

- The force provided in the table are the maximum forces occurring in one measurement point. To come to the total force in the plug-socket connection, one should multiply value this by twice the amount of cables when all points experience force in the same direction. When a torque occurs in the plug socket connection, the positive and negative force should be multiplied by the one time the amount of cables. The forces where torque occurs are marked bold in the. More detailed information on the exact forces per point can be found in the figures in appendix D.
- The resultant forces are measured from the plug onto the cable. So, a positive force in z-direction indicates that the cables are executing a vertical force on the plug-socket connection.

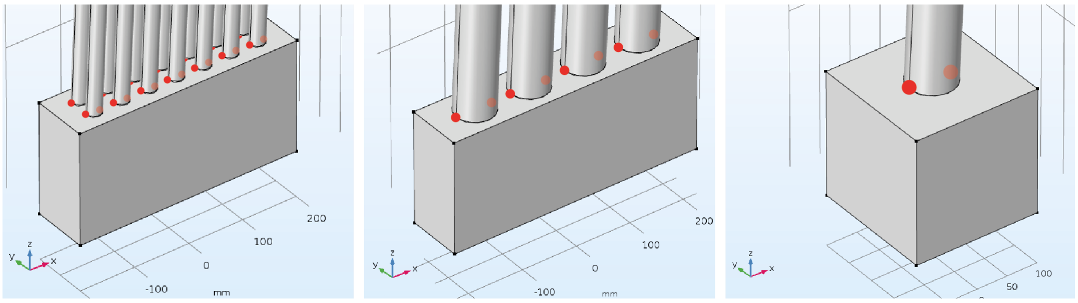


Figure 3.30: The point in the Comsol model where the resultant force is measured for the three cable configurations.

	Configuration 1	**Configuration 2**	**Configuration 3**
Motion 1, High tide			
Max. Tensile Stress [MPa]	9	22	19
Max. Resultant Force x [N]	**+24 and -18**	**+120 and -260**	**+220 and -50**
Max. Resultant Force y [N]	-65	-700	-700
Max. Resultant Force z [N]	**+25 and -40**	+200	+150
Motion 1, Low tide			
Max. Tensile Stress [MPa]	1.5	4	3
Max. Resultant Force x [N]	+9 and -8	**+120 and -130**	**+20 and -30**
Max. Resultant Force y [N]	-44	+100 and -650	+50 and -270
Max. Resultant Force z [N]	**+24 and -18**	**+400 and -350**	**+120 and -100**
Motion 2, High tide			
Max. Tensile Stress [MPa]	5	11	9
Max. Resultant Force x [N]	**+15 and -11**	**+70 and -142**	**+120 and -40**
Max. Resultant Force y [N]	-39	-400	-360
Max. Resultant Force z [N]	**+18 and -28**	+110	120
Motion 2, Low tide			
Max. Tensile Stress [MPa]	0.15	0.9	0.6
Max. Resultant Force x [N]	+8 and -3	**+80 and -30**	**+40 and -60**
Max. Resultant Force y [N]	+2 and -24	-270	+40 and -110
Max. Resultant Force z [N]	**+26 and -17**	**+210 and -140**	**+140 and -110**

Table 3.5: Overview of the results of the cable simulations in Comsol.

The cable is composed out of varying layers of different materials, and so, with different material properties. In table 3.6 the yield strength is given of the materials enclosed in the cable. Important is that the internal tensile stress of the cables does not exceed any of these values, since this implies plastic deformation of the cable. This form of damage was observed for the Stena Line charge power cable, as can be seen in figure 3.31. Plastic deformation causes possible reduced performance of the power cable and higher risk for failures. The yield strength is given for a material temperature of 20°, while the cable will heat up during charging and materials can reach a temperature up to 90°. This can decrease the yield strength significantly up to ca. 20% [59]. However, the Youngs modulus of the cable materials will decrease when these become warmer, which means that the stress caused by a certain motion is decreased. The ratio of this decrease is comparable and since the material properties in the simulation used where at room temperature, the yield strength at room temperature can be used for the evaluation [56], [63].
From the simulations results the following observations are done :

- Comparing the principle stresses found from table 3.5 and the yield strength of the materials incorporated in the cable from table 3.6, configuration 2 and 3 are overwriting some of the yield strengths and can therefore cause plastic deformation. However, one should notice that the highest stress in the cable

Material	Yield strength [MPa]
Copper (Conductor & screen)	70
XLPE (Insulation)	22
LDPE (Packing for multicore cables)	17.5
HDPE (Sheath)	23

Table 3.6: The yield strength of the materials that are present in the power cable at 20° [63],[42].

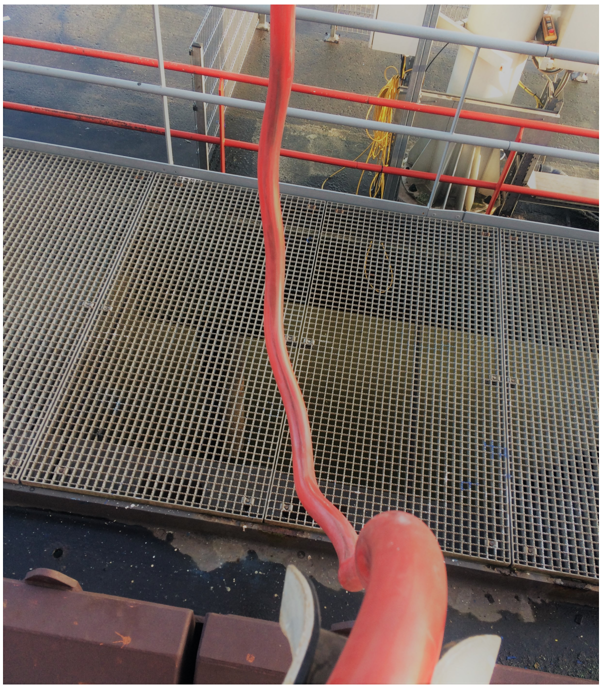


Figure 3.31: The power cable of the charging mechanism of the Stena Line which is plastic deformed.

is occurring at the outside of the cable. An impression of the stress distribution over the cross section of the cable is shown in figure 3.32. Since the cable sheath is from HDPE, this is the material in which the highest stresses will occur. All maximum stresses stay just within these limits. However for the high tide, motion 1 scenario. The difference between the occur stress and the yield strength is only just over 4%.

- Considering the resultant forces, it can be concluded that these are much higher for configuration 2, than for the other two cases. This makes sense since the stress in the cables of configuration 2 and 3 are comparable, but configuration 2 contains four cables executing forces due to these stresses, while configuration 3 only contains one of these cables. Configuration 1 has even more cables, but the stresses are significantly lower such that the sum of the forces are lower as well.

- The main displacement causing issues is the vertical displacement. This can be clearly seen when comparing the stresses from motion 1 and 2. While movement of the plug in the xy-plane only make the cable bend, movements of in the z-direction cause the cable to buckle. The results in higher internal cable stresses and resultant force. Moreover, buckling is non-linear behavior of which the consequences are hard to predict.

- For all high tide simulations, the cables behave rather like a beam than a cable. This is especially the case for the cable of configuration 2 and 3, which have a large moment of inertia compared to the cable of configuration 1. This can be clearly seen when comparing for example the resultant force in z direction for configuration 2, moving with motion pattern 1. This output is shown in figure 3.33. For the high tide scenario, the vertical force is increasing approximately linear with the increased vertical displacement. The larger peak in the first 0.5 sec of the 3m scenario, can be explained be the increasing stress due to the plug displacement while the cable behavior in the linear region. After this 0.5 sec, the

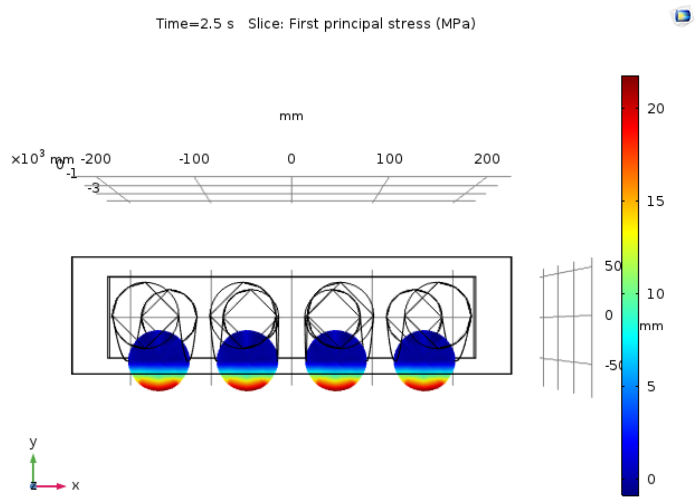


Figure 3.32: The stress distribution of the principal stress. Here shown for configuration 2, high tide scenario, motion 1.

cable is buckled and shows non-linear behavior. For the low tide scenario the vertical force output is more fluctuating over time. This is caused by the swinging behavior of the cable. As can be seen in the output, the resultant force are in this case also increased due to this swinging cable motion. Swinging motions are hard to predict and so are the resulting forces as well.

- Torque only occurs in x- and z-direction but never in the y-direction. This is probably caused by the way that the model was set-up. For configuration 2 all cables where aligned in x-direction and also for configuration 1 the cables are divided in two rows aligned in the x-direction. Therefore, the y-location is equal for most cables. However, this is probably not the only cause that no torque occurs in y-direction. Also for configuration 3, which only contains one cable, there does not occur a torque in the y-direction. The other reason for this to occur is the location of the measurement points, which are all aligned in x-direction as well as shown in 3.30. Therefore, all measuring points have the same y coordinate. This will be further discussed in the simulation evaluation.

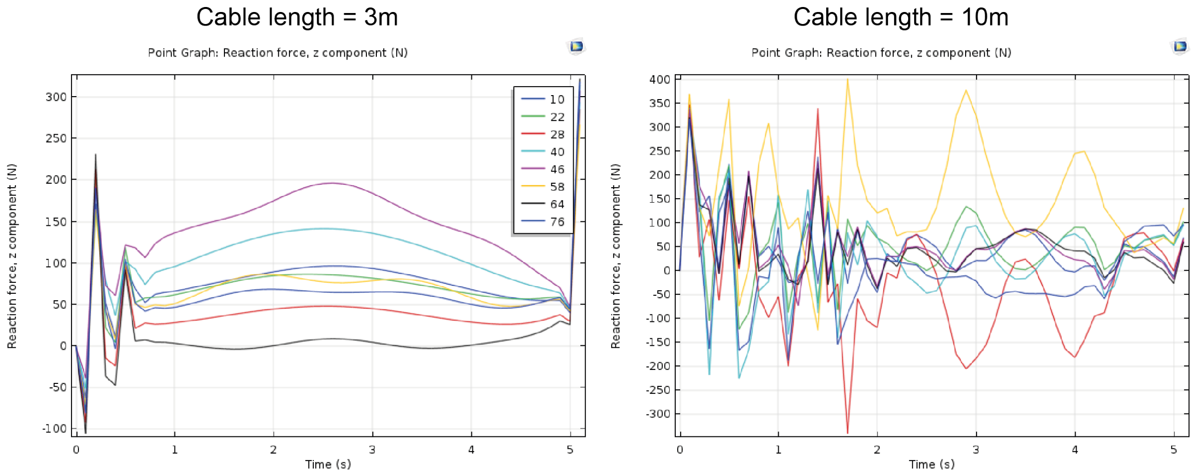


Figure 3.33: The output of the vertical resultant force (Fz) for cable configuration 2, motion pattern 1

Simulation Evaluation

The difference between the output of all simulations is as it was expected. The moment of inertia of the cables in configuration 1 is significantly smaller compared to the other two cables simulated. Therefore it is reasonable that the simulation of these cables results in the lowest internal stresses. The moment of inertia of the cables in configuration 2 and 3 are comparable. However, the copper content of the cable from configuration 2 is over 27%, while the cable from configuration 3 only contains 15% copper. Since the stiffness of copper is much larger compared to the plastic materials used in the cable, it is reasonable that the cable of configuration 2 is is stiffer compared to the cable from configuration 3. This explains that the output stresses of configuration 2 are higher for the same prescribed displacement.

For the simulation, the cable had to be modeled as a homogeneous material. Modelling all separate layer was not feasible because of the large computational power required. The properties of the homogeneous material were initially calculated by combining the properties of the cable materials according to Euler-Bernoulli. However, the conductors are not solid copper beams, but consists of many copper string with a diameter <1mm that are helix shaped bundled. When the cable is bend, the strings provide flexibility since they can move separate from each other. When applying Euler-Bernoulli this is neglected. Using these values resulted in high output and unreliable results. Therefore is was decided to calculate the elastic modulus in a different way, by using the minimum bend radius and the maximum stress allowed in the copper parts as. This information was provided by the cable supplier. Using the material properties calculated this way for the simulations, gave a more reliable output which is the one shown in table 3.5.

A finite element problem can be solved by various solvers, time steps, accuracy etc. For this simulation a multiple of solvers are examined with varying accuracy. The settings of this problem was chosen such, that each calculation could be solved by the exact same settings within a reasonable calculation time. This excludes the possibility that the difference of two simulation outputs is caused by different ways of solving instead of their different input. However, it might be that other settings produce more reliable results for a certain configuration.

Most of the output of the resultant forces, show high peaks between 0 and 0.5 sec. This indicated that the behavior at the beginning of the simulations is still linear and when the displacement increases too much, the cable will buckle and the cable behavior is non-linear. Since the final design will be made such that the cable is already buckled in its initial state, these peak values are not taken into account in the output of table 3.5.

The measuring points for the resultant forces in this simulation, where chosen on the location where Comsol provide them. However, measuring on other points can provide other insides. As seen before, most measuring points have the same y-coordinate since all points are distributed on the x-axis. For future simulations it would beneficial to check the resultant forces on other y-coordinates, such that more insight is created in the overall resultant forces.

Finally, the situation that is simulated is strongly non-linear. The non-linear behavior of structures is in general caused by imperfections. This behavior is always hard to predict, since there are no imperfections in the computer. The cable shape was modelled slightly bend, such that buckling will easily occur. However, real life experiments are required to test the actual behavior.

3.8.2. Final design

From the simulation results, configuration 3 is selected as the desired solution. Configuration 2 is judged to be not suitable since the simulation for the high tide, motion 1 scenario, provided internal stresses in the cable which are only 4% under the yield strength of the sheath material. This is considered to be not a sufficient safety factor. Moreover, the resultant forces of this configuration are significantly higher compared to the other configurations. Configuration 1 would be a feasible option, since the stresses and forces occurring are the lowest of all cable configurations that were simulated. However, this system requires the use of fourteen cables. It is expected that this will result in other, not flexibility related, issues when the system is in operation. For the low tide scenario for instance, it was observed that the cables will perform a swinging motion. When using fourteen of these swinging cables, it likely that these get entangled. Therefore, the HV cable will result in a more reliable charging mechanism compared to the application of configuration 1 or 2. However, also for the HV cable, the resultant forces and internal stresses in the cable are significant. The design has been modified to decrease this as can be seen in figure 3.34. The top of cable was fixed in the simulation, which required the cable to absorb all the displacements of the socket. As seen before, the vertical displacement was the most critical motion. Reducing the amount of displacement that should be captured by the cable, will reduce the internal stresses and resultant forces significantly. Therefore, in the final design top of the cable is not fixed to the crane, but should be able to vary in height instead. Doing so, only a part of the vessel movements in z-direction has to be absorbed by the cable. This could for example be achieved by supporting the cable with a spring as shown in figure3.34. However, more research is required to exactly define this supporting structure.

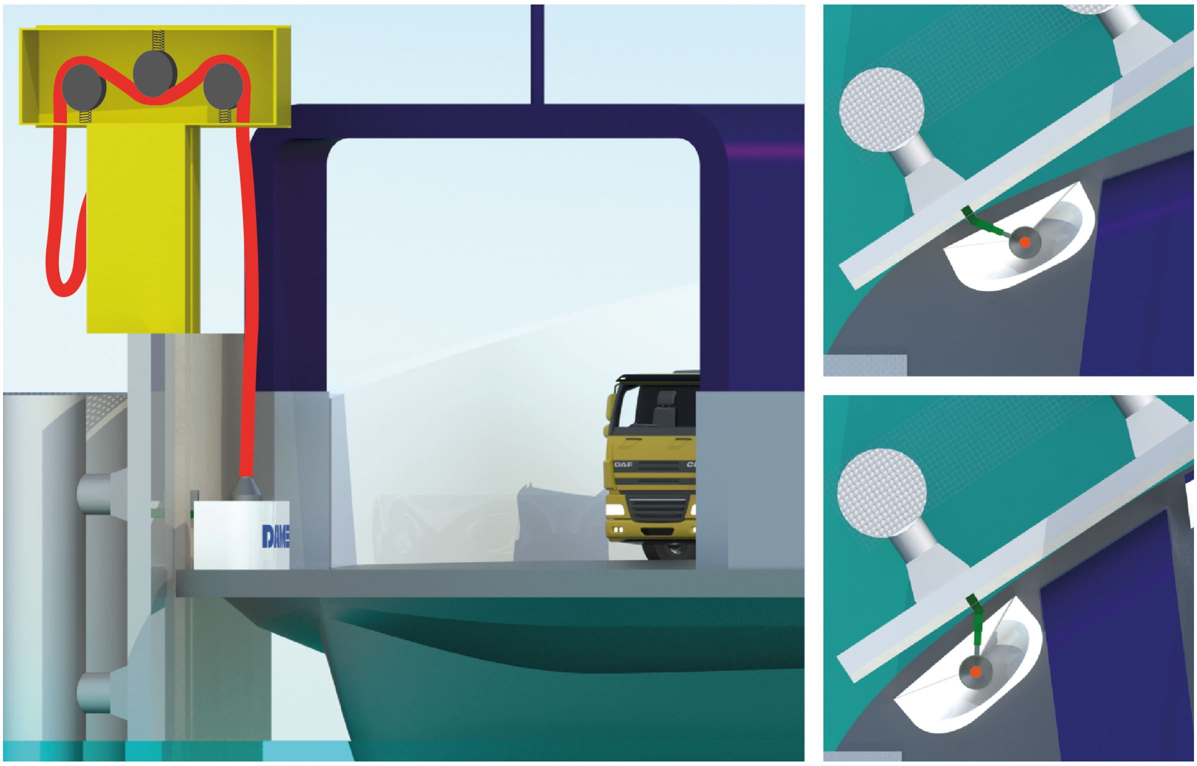


Figure 3.34: An impression of the final design, showing the ability to deal with misalignments between the vessel and the shore and an impression of how the bearing of the cable could be height varying.

As a consequence of using the HV cable, the charging mechanism will charge with HV and so the an onboard transformer and rectifier should be installed on the vessel. This will occupy space on the vessel and add significant weight which is undesired. However, the reliability of a LV system is expected to be such poor, that this is even less desirable. It is therefore advised to investigate the possibilities for using a HV charging mechanism.

3.9. Conclusion

The there where two main goals for doing this case study. First of all, a charging and mooring mechanism should be designed that is suitable for the BC Ferries. All steps of the design method from Engineering Design Method, by Nigel Cross [24], where conducted to do so. In the second step of the design method, the main and sub-functions for both mechanisms where determined. This showed that is was hard to integrate both systems into one mechanism, due to the required flexibility of the charging mechanism on one hand, and the required stiffness of the mooring mechanisms on the other hand. Because of the limited time available for this research, the mooring mechanism was rejected out of the scope of the case study.

The case study was continued by determining the requirements. This was an intensive step in the process since most requirements are effecting multiple fields of interest. To provide a more clear overview in these requirement, they were divided in three categories. The functions and requirements were compared to the commercially available charging mechanism from chapter 2, after which it was concluded that no existing product is suitable for the BC Ferries case. The gap between these is the combination of the functions: compensate the tidal difference, deal with misalignments and provide flexibility for vessel motions. These functions had therefore the main focus in the design phase. In this design phase, a range of mechanisms was conceptualized with different working principles, of which three were elaborated on in more detail. Evaluating these concepts showed that a crane-like mechanism is the most favorable solution for the BC Ferries case. Extensive research was done to the power cable flexibility, since existing chargers showed this to be a critical aspect. FEM simulations were done for varying power cables, water level and vessel motions. From this simulation it is concluded that the HV cable is the most beneficial solution and therefore it is advised to investigate the possibility to install the required transformer and inverter on board. For the LV cable only one scenario that is simulated would be sufficiently flexible. This is configuration 1, in which fourteen parallel power cables are used. However, for this scenario other difficulties are expected. It is advised to further optimize the simulation and elaborate on the simulation of this cable before actual implementation. In this simulation only the minimum and a large amount of LV cables have been analyzed. However, there might be other scenarios feasible using LV cables, for instance when using a cable with an outer diameter in between the one from configuration 1 and 2 and so, a total amount of cables between four and fourteen.

Up till now, only the standards flexible shipping cables have been used for the charging mechanisms of electric vessels. However these are ordinary power cables classified as flexible by IEC 60228. This is classification is purely based on the ratio between the diameter of the copper wires in the conductor and the total diameter of the conductor. However, the classification flexible does rather imply that the cable can be bend in a certain position and leave it that way. This does not state anything on the ability to withstand the continuous motions of the cable [46]. For other industries that demand for high flexibility of cable, such as offshore installations, a different kind of cables are used called umbilicals. In these umbilicals all conductors, optical fibers and other strings are aligned in an helix around the cable centerline as shown in figure 3.35. This helix alignment of the strings allows a higher flexibility of the entire cable compared to power cables where all strings are aligned parallel to the cable centerline [66]. These umbilicals are mainly used to transfer energy and data from an off-shore windfarm, which can transfer over 600 kV. Their dimensions are therefore not in proportion to the cable of a charging mechanism, however the way that the cable layers are composed could possibly also be used for smaller power cables. These have not been found to be commercially yet, probably since the demand was just not there until the introduction of electric vessels. Another cable that might be worth considering is a liquid cooled cable, of which currently a view have been developed to charge electric vehicles. In these cables, the conductor of the cable is cooled by a liquid flowing around the conductor. Since cooling by flowing liquid is more efficient with respect to air, the current flowing through a conductor without overheating the conductor can be higher in this case. Therefore, the required conductor size for a certain current transfer is decreased and the cable flexibility for this specific current is increased.

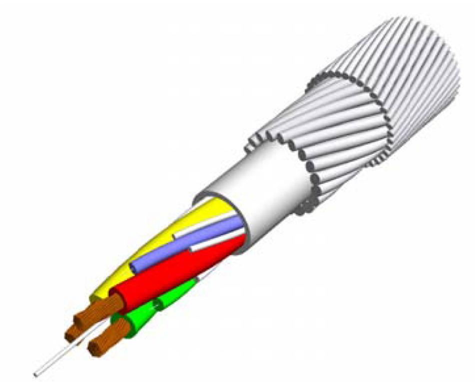


Figure 3.35: The layout of an umbilical that used for offshore power transfer [76].

The second goal of the case study was to gain knowledge in the influential factors when selecting a charging mechanism for an electric vessel. The case study has shown that finding a suitable charging mechanism is a complex and time demanding procedure. This is also the reason why this case study occupies the larger part of this entire report, although doing the case study is not the main goal the research. It is rather the long route that has to be taken the achieve the main goal. Finding a suitable charging mechanism requires to take into account numerous requirements for different aspects such as the installation location, the power demand, freedom of movement and varying customer desires. These requirements can not be considered separately from each other since they all influence one another. Do to the large amount of influential aspects and the large dependency between one another, it easy to get lost in a large list of requirements without any structure. To ease this process of setting the correct requirements, the guideline should provide a clear overview of all requirements that should be set and in which order. Doing so, there is ensured that no aspects are overlooked and that the list of requirement is clear for the engineers to work with. The development of this guideline is further discussed in the following chapter.

4 Design guideline

In this chapter the generic guideline for the selection of a charging and mooring mechanism is set up. The goal of this guideline is first clearly identified in 4.1. This was general identified in chapter 1 and will be discussed now more extensively based on the experiences gained during the case study. Afterwards, the layout of the guideline will be established in 4.2. The general design method from [24] that was used for the BC ferries case study will be revised to see what parts of the method were help full and which parts could perhaps be modified, left out or be added to the guideline. The final guideline will be validated by another case study, searching a charging mechanism for an electric tug boat. This is presented in 4.3.

4.1. Goal of the guideline

The main issue that Damen is currently facing in the development of electric vessels, is that no standardized solution is available. For the hand full of electric vessels that are currently operating, one of a kind solutions have been developed. This causes that designing an electric vessel is an extensive and time consuming process. Since the demand for electric vessels is expected to increase rapidly in the near future, so will the demand for charging and mooring mechanisms as well. The main goal of the guideline is therefore to decrease the selection time for a suitable charging and/or mooring mechanism. This will save time and costs during future projects, which will provide Damen a strategic advantage in vessel tenders. To decrease this selection time, sub goals have been set up which should be a tool to achieve the main goal. These sub goals were established based on observations form previous projects done within Damen.

The first striking observation with respect to the current procedure at Damen, is that every project team working on an electric vessel is starting more or less from scratch. This causes that a project starts with time consuming meetings in which the system requirements should be determined. Since the requirements of the mechanism incorporate many different fields of interest and can be strongly related to one another, is it easy to lose track of all aspects and their implications to other aspects. Also, is it hard to determine of what the main requirements are and which are subordinate. The guideline should provide a clear overview of the requirements that should be determined and the relations between them. A clear order of setting the requirements should be defined. In this order it should become clear what the consequences of certain decisions are for later requirements.

Another consequence of the this "starting from scratch procedure", it that there is generally little knowledge within the project team of the available charging and mooring mechanisms. Therefore a project for a new electric vessel includes generally orientation meetings with multiple companies (ca. 10) to discuss the concepts that they can offer. After various meetings with each company it is considered which can provide an actual solution for the specific vessel. The guideline should provide an overview with all concepts available and their characteristics. While setting the requirements, this overview can be used to check which system would be suitable and which would not. Knowing this, only the companies with a potential solution have to be approached. And because the project team has already some knowledge on the system provided by this company, the meetings can directly more into depth.

Project teams at Damen for new built vessels consist generally of people from different departments such as, design & proposal, electrical engineering, project management and structural engineering. If they go through the guideline as team, it should become clear that decisions for one aspect of the system can have major consequences to another aspect .Getting this in one overview ensures that the all members of the project team are working in the same direction. This should prevent people moving in a certain direction because this is preferable in their field of interest, but focus on the greater good.

4.2. Layout of the guideline

To design a charging and mooring mechanism for the BC Ferry, the design method from Engineering Design Methods was adopted [24], shown in figure 4.1 below. This method is now evaluated based on the experiences of the BC Ferries case. Four main observations where done for this method, which should be modified to specifically suit the purpose of finding a charging and mooring mechanism for electric vessels. Based on these points the layout of the final guideline is determined.

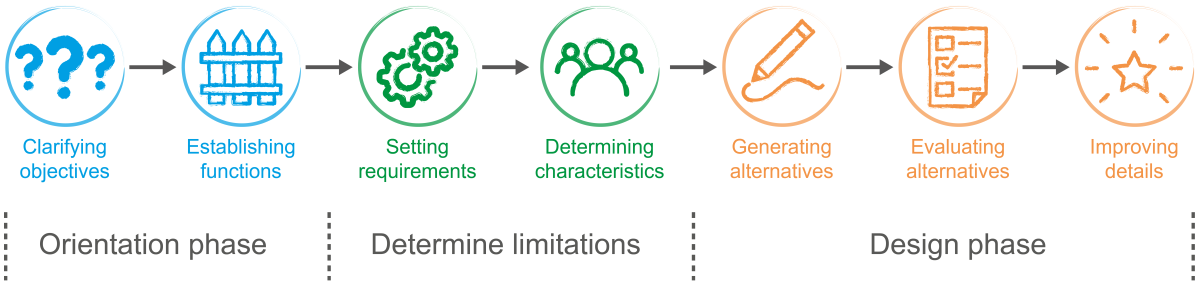


Figure 4.1: The design method that has been used for designing a charging mechanism for the BC Ferry [24].

1. The orientation phase does not add value. The goal of this phase is to gain insight in the subject and the objective of the system that should be designed. Generally at Damen, for the design of a new electric vessel, the vessel is first designed before a charging and mooring mechanism is selected. Therefore the orientation phase is already executed during the design process of the vessel itself, the engineers get already familiar with the subject such that no additional orientation is required once selecting a charging and mooring system.

2. The design part is effective if you want to develop a charging or mooring mechanism, but also a time consuming process and it is likely that Damen will not be using this for future projects. Damen is a shipyard and not a charging of mooring mechanism factory. When it appears in future projects that no suitable charging or mooring system exists, Damen will probably not design this themselves. What is more likely to happen, it that Damen presents their requirements and the gap with the existing systems to a company specialized in these products such as Cavotec, Stemmann-Technik or ABB. This company will then develop a system which does satisfy the demands.

3. Setting the requirements has appeared to be an important, but also complicated step. While this step is straightforwardly described in the design method, this seems more complicated in reality due to the variety of aspects that should be taken into account and the dependencies between the requirements. To ease this process a clear structure in the requirements is desirable. The guideline through the requirement step should therefore be extended with a process on how to structure the requirements. The way this is structured is described below in subsection 4.2.1.

4. The design method assumes that a new product is designed in any case. This is not the goal of the guideline. The guideline should make clear what exact mechanism is demanded and based on this, it should be determined if an existing product is satisfying or whether a new product should be developed. The final guideline should therefore also present the existing systems that could be used and

support interaction between the requirements determined and the existing systems.

Based on these four observations, the layout of the guideline is constructed. This is graphically shown in figure 4.2. It starts of course with a project, which is the initial reason of looking at the guideline. This project needs either a charging mechanism, a mooring mechanism or both. The first two chapters focus on how to determine the requirements for these systems. These chapters may look comparable but are written separately on purpose for mainly two reasons. First of all, because a project does not necessarily require a charging and a mooring device but possibly needs only one of these. Moreover, it is likely that the requirements for the charging and mooring mechanism differ while the question asked is equal. For example, on the question if the mechanism may be manual operated, it is likely that one of the systems should be automated while the other does not. By separating the requirements for charging and the mooring system, it is ensured that requirements will not get mixed up. An overview of the existing charging and mooring mechanisms is provided in the appendices. While setting the requirements, the user of the guideline should check if there are systems available which satisfy these. This can either result in one or multiple products that are suitable for the case or the conclusion that no suitable solution is available yet. In the first case the supplier of the system(s) is contacted to further negotiate. In the second case, the gap between the requirements and the existing products should clearly be identified. This is generally not one requirement but rather a set of requirements which make the existing mechanisms not suitable. Once this set has been determined, a supplier of charging or mooring mechanisms can be contacted to request for a new product.

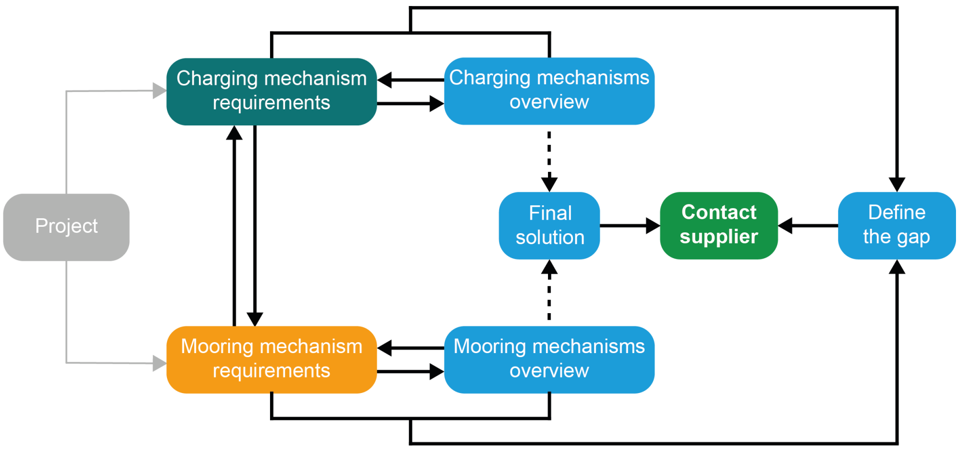
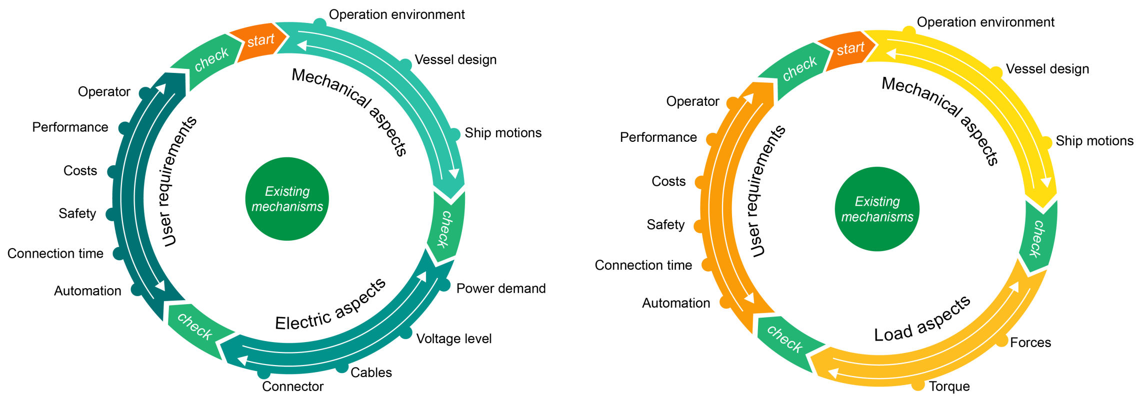


Figure 4.2: The layout of the guideline for finding a charging and mooring mechanism for an electric vessel.

4.2.1. Establish the requirements

As stated before, setting the requirements is complicated due to great dependency between the requirements and the variety of aspects that should be taken into account. Therefore a clear structure is desired to ease this process. The structure of the first two chapters, in which the requirements are determined, are schematically shown in figure 4.3a and 4.3b. For both chapters the set up is equal. The requirements that are relatively easy to determine are placed first, the requirements which are more time consuming are determined later. Doing so, one can quickly check if there are suitable mechanisms based on the first requirements and no time will be wasted on complicated calculations while the projects might be unfeasible or unprofitable.

For both, the first step is to focus on the mechanical aspects. This is based on the operating environment, e.g. a port, the vessel design and the ship motions. The requirements that follow from these factors are for instance the location where the system can be installed, the maximum dimensions of the system and the required movement flexibility. This is the first step since these can generally be determined by simply observing the operating environment and the vessel design and no complicated calculations are required. Determining the ship motions can be some more time consuming, however the sea keeping calculation required is relatively simple. Moreover, in the case of a standardized vessel there are probably already simulations available which only require minor adjustments. It can be seen in the flow chart from figure 4.3a that within in this aspects, arrows are pointed back en forth between the categories. This is to stress the relation between the categories and to show the engineering that one should look back once in a while to the determined requirements. For instance, one can imagine an separate location for the charger in shore and on board, but these should match of course to make it work. After this first step, one should check if there are existing mechanisms satisfying these requirements. If there are not systems available from this point already, one should wonder if the requirements are too tight or if the project is even feasible. If this does not seem feasible, minimal time has been wasted on this project. If feasible, the second step follows which demands some more calculations. For the charging mechanism this includes the electric aspects, for the mooring mechanism this step focuses on the forces that is should be able to withstand. Again after this step is should be checked if an mechanism is existing which satisfies the requirement and if it is feasible. If so, the last step is to look at the user requirements. These are requirements that do not concern if the system will be functioning for a physical reasons, but whether the product is also commercially desirable. This includes for instance the level of automation, the safety measures and the financial limitations. This is placed last in the circle since this can be a time consuming process when these should be determined in consultation with a customer that can be located all over the world. Furthermore, this way a project for a new electric vessel can start when there is not contracted a consumer yet. When also these have been determined and the entire set of requirements is completed, it should be checked if there are still suitable of the shelf products available. It is likely that this is not the case after going through this circle just once. Form here the iteration of the requirements starts, in which the requirements should be revised and modified to check whether there would be a suitable system available for this new set of requirements. For instance for another location of the installation or for a different power level of the charger. Iteration of this circle should continue until either a suitable product has been found, or until it can be concluded that no suitable mechanism is commercially available.



(a) The iteration circle to determine the requirements for the charging mechanism.

(b) The iteration circle to determine the requirements for the mooring mechanism.

Figure 4.3: A graphical overview of the structure to determine the requirements for a charging and mooring mechanism

These iteration circles are incorporated in the guideline. In this guideline, additional information is provided on which requirements specifically should be defined per category and what the influential parameters for these requirements are. Per category there is also a table in the guideline that should be filled out with the determined requirements. These tables are included for multiple reasons. First all, it provides a checkpoint for the engineers going though the guideline. By filling out this table it is ensured that no requirement is forgotten or left out. Furthermore, clear documentation of the requirements determined, help to keep all engineers within the project team on the same level and prevent misunderstandings. Lastly, most table provide the opportunity to fill out multiple options. This shows clearly that multiple options could be possible which stimulates the engineer to think further than just the first option imagined. The complete guideline can be found in appendix F.

4.3. Guideline validation

A new project at Damen is the development of an electric Reversed Stern Drive tug boat (RSD). The RSD, shown in figure 4.4, is a standardized design of Damen of which multiple diesel driven version have been delivered world wide. Now the first electric version is under development. Since this project just started, the guideline was used to verify whether this would be helpfull to select a charging mechanism for this vessel. Since the vessel type and operating conditions of the electric tug are completely different from the BC Ferry case, this provides a good opportunity to check if the guideline was generic enough for another vessel type. It was also tested if the guideline is clear and complete to people who are not familiar with the guideline yet. Next up test procedure is described in 4.3.1. The test is evaluated in 4.3.2 by observations done during testing and by feedback from the engineers performing the test.

Figure 4.4: The RSD Tug 2513 developed by Damen [36].

4.3.1. Test Procedure

The project team of the electric tug consists of ca. 7 Damen employees with various functions such as a mechanical engineer, an electrical engineer, a project manager and development engineers. This team already began some months ago to start up the development the an electrical tug boat. Now that this project is fully running they are starting to focus on the charging mechanism that should be sold in combination with this vessel. There is no need to search for a mooring mechanism for this vessel, since it is designed to moor manually. During the test was no contracted customer yet, but various parties have shown their interest towards this vessel.

At the start of the test, the guideline was presented to the project team. The team went through the entire iteration circle during a session of ca. two hours. During this session all requirements and possibilities were documented. This document could be used to check what was clearly understood of the guideline and which aspects should be need more clarification.

4.3.2. Test Evaluation

In section 4.1 three main goals of the guideline where determined. The test of the guideline will be evaluated based on these goals to check whether it does fulfill its goals. To recap, the goals of the guideline are:

1. Provide insight in the necessary requirements and their relationship.
2. The entire project team working in the same direction.
3. Main goal: Decrease the selection time of the charging mechanism.

Provide insight in the necessary requirements and their relationship.
Before the test, the team had already some requirements for the charging mechanism in mind. For instance the location of the onboard socket connection. This was chosen on the side of the deckhouse simply since here was space available. The iteration circle showed them the consequences of choosing for this specific location, which where not taken in mind before. This location would namely be next to the living space of the captain and to the entrance of the deckhouse which could cause safety issues. Furthermore, the the connection would obstruct the on deck walking area. This guideline showed these consequences which encouraged the team to consider other locations. The same applies to the charging power. This was imagined to be 3MW, basically since this is the maximum power that the onboard battery pack can handle. The guideline provided insight in the consequences of this power level, such as the cable weight and flexibility, which got the team to consider other power levels which are suitable for the operational profile as well.

The entire project team working in the same direction.
During the test the entire project team was present, which are mainly engineers with varying specializations. The team meets a couple of times per week but outside these meetings, every engineer is focusing on his or her part of interest. Of course this is required to make the process efficient and doing everything together would not be beneficial. However, it is important to keep the whole team up to date on the current status of all the aspects since all fields of interest are depending on one another. A good example of this is for instance the charger power demand, which was determined to be 3MW by an electrical engineer. While discussing the power demand, and whether this could be lower to increase the flexibility of the cable, it appeared that not the entire team was up to date why 3MW was chosen and what was actually required from an operational point of view. Using the guideline stimulated to engineers to provide some additional information on their decisions and argue on whether this decision is also feasible form other points of interest.

Decrease the selection time of the charging mechanism.
While setting the requirements, the overview with existing mechanisms was consulted regularly as the iteration circle prescribes. After setting the mechanical requirements only, the majority of the the existing mechanisms was already rejected. This was mainly due to the requirement that the tug boat should be able to moor with a margin of ca. ± 1m of the imagined mooring location. Since most charging mechanisms are designed for ferries which always moor at the exact same location, these do not support margins of this level. Going through the entire iteration circle resulted in a clear idea of what a suitable solutions should look like. A manual crane, like one from figure 2.6a, came out to be the preferred solution. The main arguments for this are the large the relatively large alignment space between the vessel and the shore and the easy manual connection because of the vertical plug connection. The crane from 2.6a does not provide the demanded power level, but this is a design aspect that could possibly be modified by the supplier. After the guideline test, the supplier was contacted for the development of a comparable crane system for a higher power level. Negotiations between Damen and the supplier are currently going on.

The guideline validation proceeded well and it showed immediately its benefits. All goals that the guideline was supposed to achieve where obtained. The guideline provided a clear overview of all influential aspects in selecting a charging mechanism and the relations between those became more clear than it was before. This test resulted in a preferred system immediately which is now further discussed. Therefore the guideline can be stated the be beneficial to decrease the selection time for a system. The team was clearly working in one direction and focusing all on the global purpose of the system. However, the were no clear disagreements before the test of the guideline. Therefore it is hard to validate that the use of the guideline improved the focus on the global goal, but it can be stated that it stimulated to do so. The guideline was originally developed based on the knowledge of a case study on passenger and vehicle ferry. The test on the electric tug validated that the guideline is generic enough for varying types of vessels. What was interesting to see though, was that the crucial aspects where very different from the BC Ferry case. The space in the port was an important aspects for the ferry for instance, since most locations must remain free for other vessels or for vehicles and passengers. For the electric tug however, this is mooring with its side along the quay and there is no traffic on and of the vessel, so plenty of space if available in this case. Also the connection time is for a ferry far more important compared to a tug boat, since this is sailing on a tight schedule. For the tug boat on the other hand, people are actually living there for multiple days or weeks. Exposure to the inductive field becomes in this case far more important compared to the ferry when humans are only exposed for a couple of minutes. However, this difference in priority does not effect the demanded order of the requirements. However, the time spend on a certain category will probably differ per vessel.

5

Conclusion and recommendations

In this chapter first the conclusion will be given regarding the main goal and sub-goal of this research in section 5.1. In section 5.2, recommendations for further research to continue on this subject is provided.

5.1. Conclusion

The main goal of this research was to develop a generic design guideline for selecting a charging and mooring mechanism for electric vessels. To do so, an engineering design method was selected form literature and applied to a case study where a charging and mooring mechanism was required. The knowledge gained during this case study was used to adapt and specialize the initially selected design method to be applicable for selecting a charging and mooring mechanism for electric vessels. The case study is an extensive step in this research. Finding a suitable mechanism requires to take into many factors from different fields of interest, where these are often related within one another. This makes it easy for an engineer to lose the overview of all requirements and miss some important factors. Three objectives that the guideline should fulfill were defined, based on the experiences from other projects within Damen on electric vessels. This contains one main objective and two sub-objective to support the main one.

- *Decrease the selection time of a charging and mooring mechanism.* Since the demand for electric vessels is expected to increase in the near future, the demand for these systems will increase as well. The first projects at Damen on electric vessels included much orientation to companies in this business and the products they have developed. The guideline should decrease this orientation time significantly which results in shorter delivery times. This can provide Damen a favorable position with respect to other shipyards in vessel tenders and will result in reduced developed costs for the vessel.
  - *Provide insight in the necessary requirements and their relationship.* The BaCO research at Damen and the case study from chapter 3 showed that the requirements for a system are often related to one another and therefore decisions on one aspects can have major consequences for other aspects. Providing structure for all requirements ensures that a clear overview of the requirements is maintained during the project and no important aspects are left out.
  - *Stimulate the entire project team to work in the same direction.* Since every member is in a project team with its own specialization, it can occur easily that members are primarily focusing on what is beneficial for their own field of interest. The guideline should stimulate that all engineers are concentrating on the greater good.

To realize these goals, the guideline provides a structure with all requirements that should be determined and in which order. This ensures that the list of requirements is accessible and that all important factors are noticed. The order of the requirements is determined such, that the requirements that are easiest to determine are set first. The time demanding requirements are set later in the process. An overview of the existing mechanism is included as well, which should be consulted frequently to check whether a suitable mechanism already exist, if a new system must be developed or the requirements should possibly be modified. After setting the first and easy requirements, the overview can be checked for possible solutions. When it appears that this project is unfeasible or unprofitable, only little time was wasted on this project.

The guideline was validated by applying it to a new case study, an electric tug boat. Before the guideline was tested the project team had already determined some requirements, but it was clear that not all consequences of these decisions where taken into account. A good example of this was the location of the onboard socket. This was already imagined in a certain place, but it was not thought through that the vessel can than only moor with one specific side to the quay in this case, while multiple mooring configurations might be desired. The guideline provided this insight by showing the relation between the port and the vessel layout. The test of the guideline was an interactive session where the team members collaborated well and explained their thoughts on specific aspects from their point of interest. Doing so the entire team was focusing on the great good and not on specific aspects. Although there were not specific conflicting thoughts within the project team before the test of the guideline, it did stimulate to keep focusing on the global goal. The test of the guideline resulted in one system that the project team was enthusiastic about, although it does not provide the desired power demand. The supplier of this system was contacted about this product whether this could be redesigned for a higher power supply. Negotiations between the supplier and Damen are currently going on. The test of the guideline validated the guideline since it fulfilled its purposes during the test. The necessary requirements and their relations became more clear than they were before, it stimulated the project team to collaborate on the greater good and the selection time of a charging mechanism was decreased with respect to the BC Ferries case since the guideline provided a possible solution straight away. The guideline was shown to be generic since it was applicable for a tug boat with the experienced based on a passenger and vehicle ferry.

The sub-goal of this research was to design a charging and mooring mechanism for the BC Ferries case. It appeared hard to combine the design of these systems due to the required stiffness of the mooring mechanism on one hand and the required flexibility of the charging mechanism on the other hand. Because of the limited time available for this research, the design of a mooring mechanism was eliminated from the research scope. For the design of the charging mechanism, there was primarily focus on the functions which were identified as the gap between the existing mechanism and the requirements for the BC Ferries case. These are the ability to provide flexibility, to deal with misalignments and to compensate the tidal difference. Also the technology for energy transfer was included, since this decision has a major influence on the other critical functions. Various mechanisms have been conceptualized of which three have been chosen to elaborate on and check its preference for the BC Ferries case. After evaluating these three concepts, the most fitting system for this case showed to be a conductive crane charging mechanism. The plug is connected to the wind wall and is this way protected from a swinging motion. The plug is lowered into a funnel shaped socket, directing the plug always to the socket in the case that the vessel and port are misaligned. This passive connecting method does not depend on any optical sensor and is therefore expected to be less sensitive to external disturbances. The plug is vertical displaced on the wind wall, such that the tidal difference can be compensated. The flexibility of the mechanism has to be provided by cable flexibility. Since this aspect causes often operational failures on the currently existing mechanisms, extensive research is done to select a cable that can provide the required flexibility. The flexibility of three cable configurations was simulated for varying operating conditions. These simulations provided two cable configurations that are feasible. One of these is LV cable for which fourteen parallel cables are required, the other configuration contains one HV cable. For operation with fourteen parallel cables other difficulties are expected. The cables can for instance become entangled in their swinging motion that is cause by the moving vessel. Therefore the HV cable is selected for the final design and it is advised to investigate whether the required onboard equipment can be installed. Furthermore the case study showed that especially vertical displacement of the plug results in high stresses in the cable, due to buckling of the cable. In this simulation the top of the cable was fixed and therefore the entire vertical displacement of the plug has to be absorbed by the cable. In the final design the bearing of the top part cable is flexible, such that the vertical displacement is captured only partly by the cable and partly by the bearing.

Referring back to the sub-goal, to design a charging mechanism for the BC Ferries, a conceptual design was delivered. More research is required, before this design can actually be developed. The necessary research contains for example the springs required in the beam connecting the plug to the wind wall, the bearing of the cable in the crane and the construction dimensions.

5.2. Recommendations

The guideline for selecting a charging and mooring mechanism for electric vessels was based on the knowledge gained during the case study of a ferry for passengers and vehicles. This guideline was validated afterwards for the selection of a charging system of an electric tug. These are two vessels with complete different functions but the iteration circle for the requirements and the appendix with available mechanism was applicable to both. However, since the development of electric vessels has only started since 2015, major developments within this field are expected in the near future [28]. During future projects it is important that the guideline will be updated based on additional experiences from future projects. Also the amount of charging and mooring mechanism is expected to increase due to the increased demand for electric vessels. The overview of the available mechanisms should be updated once new mechanism are launched, such that the guideline remains to be a reliable overview of the technologies available.

The development of electric vessels is a relatively new subject and therefore no standardized or generic charging solution is developed yet. All solutions available have been originally designed for a specific case. During this research there was focused to developed a solution which was generic and automated at the same time. This appeared to be difficult since the automation of a system is strongly related to the vessel design. Additional research should be done make the design easier applicable to other vessels or to investigate whether another design could possibly be more suitable as generic mechanism for all kinds of vessels.

The performance reliability of the system majorly depends on the flexibility of the charging mechanism. In the case of a crane construction, this flexibility of the charging mechanism is primarily determined by the cable flexibility. This cables behavior was analyzed in a FEM simulation. This simulation included the buckling of the cable, which a strong non-linear process. Non-linear processes are hard to determine by simulations since these occur always due to imperfections in the material. Therefore practical experiments to the cables should be executed the verify the cable simulations.

During this research it appeared that only little research is done to the flexibility of cables with a relative high current transfer. A company selling flexible cables, according to IEC60228, was contacted for the material properties of the insulation and sheath layer [46]. However, properties that are crucial for the cable flexibility, such as the Young's Modulus, where unknown. Power cables are nowadays determined the be flexible based on the stranding level of the copper conductor. However the material properties of the other layers within the cable, or the alignment of these layers are determining the cable flexibility as well. Research is done to the flexibility of the material of the non-copper parts [12], however this generally assumes only time to time motions of the cable while the cable is in this case moving continuously during charging. Continuously moving power cable have possibly not been research extensively until now since there was never the demand for it. In this field of interest only research was found on umbilicals, transferring power and data from off-shore wind farms to the coast, which also includes various FEM simulations. These are continuously moving power cables as well, but because the large power level that is transferred, the dimensions of the cable are not comparable to this scenario. More research should be done to the influential parameters of the cable flexibility and how this flexibility could possibly be improved.

When speaking about continuously moving objects, an engineer directly thinks about fatigue. The simulations done in this research, have only focused on the ultimate strength of the cable to gain insight in the behavior of different types of cables. However, fatigue will come into play when this charging mechanism as to be operating for multiple years. Additional research to the possible fatigue damage of power cables, would be beneficial and provide a more complete insight in cable performance of the possible configurations.

Another possible improvement for the FEM simulation that was executed, is to included the plug dimensions and weight in this simulation. For the simulation done, only the cable itself was modelled. This provided a clear insight in the the forces that can be expected in the plug-socket connection caused by the cable. However, in chapter 2 it was seen that various systems experience troublesome forces in this connection due to the moment of inertia of the plug. To gain more insight in the total forces that might be expected in the plug-socket connection, the dimensions and weight of the plug should be included in the simulation as well. This will not effect the internals stresses of the cable.
The design resulting form the case study is a rather conceptual design and not ready for development yet. An important aspects that should be researched is for instance the beam connecting the plug to the wind wall.

This beam is locked in its neutral position when the vessel in not in the port. When the vessel arrives, the beam is unlocked en moved downwards. Since the beam can deform do to the various springs incorporated in this beam, the plug is directed towards the connection point by the funnel shaped socket. The drive for this vertical displacement is not designed yet and should be investigated. Also the precise dimensions and spring properties of the beam should be researched. Another aspect of the design that should be elaborated on is the socket design. Due to the funnel shape, it is currently sensitive for water ingress which might cause safety issues. A protection for this socket should be designed, such that no water or other objects can enter the socket while it vessel is sailing or during charging. Furthermore, of course the aspects that were not in the focus of this research should be studies before this system can actually be build, such as the construction on the crane, the plug and socket that is used and the control system of the charging system.

Automated mooring mechanisms were developed already before the introduction of electric vessels and various generic products are available, of which the Automoor of Cavotec is the most established technology. However all generic automated mooring systems have to be installed on the side of the vessel, which was not feasible for the BC Ferry and therefore no system was available. Additional research could be done to design an automated system that can also moored the vessel on its rear ends.

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Appendices

A

Vessel design

A.1. Hullform

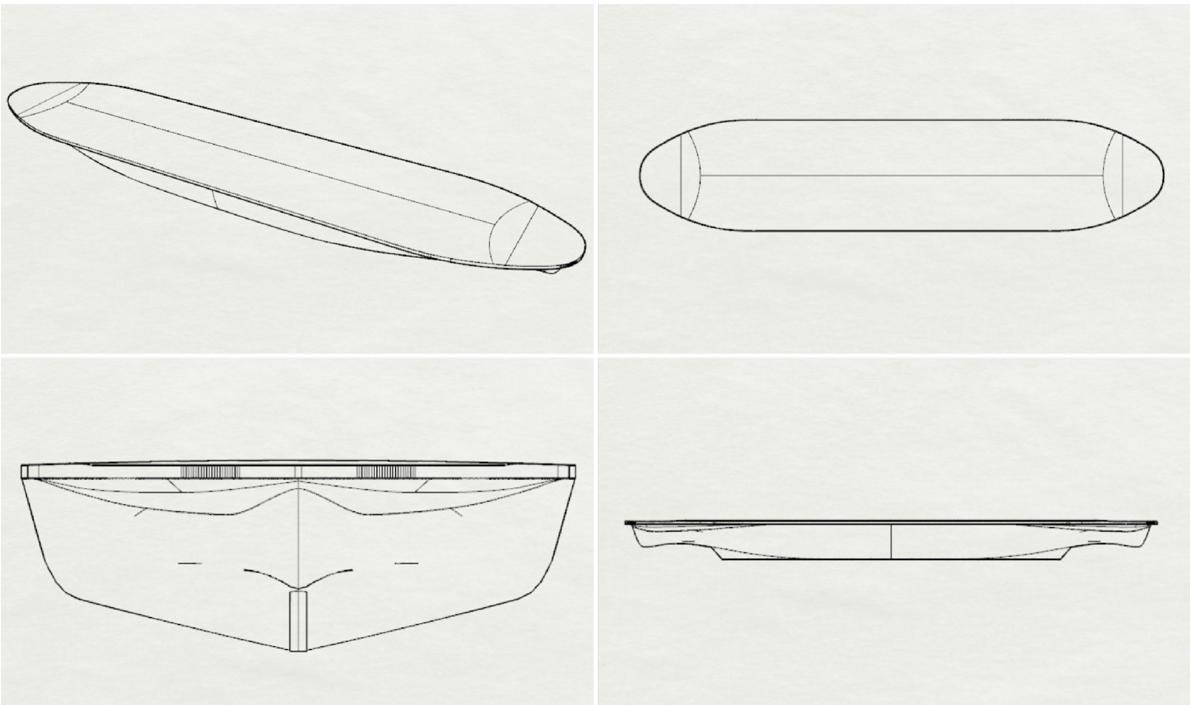


Figure A.1: Impression of the hullform as used in Qship for the Shipmo analysis.

B

List of requirement

B.1. Mechanical aspects

B.1.1. Operating environment

- The vessel should dock and charge in the standardized ports of BC Ferries, see figure below. Red items are part standard for each port.

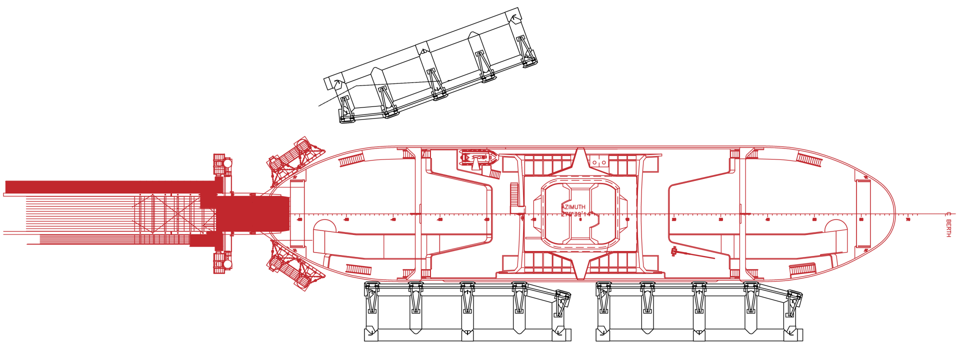


Figure B.1: The port layout of BC Ferries. The red marked items are equal in each port.

- The charging and mooring mechanism may not obstruct the ramp for passengers and vehicle driving on and of the ramp.
- The charging and mooring mechanism may not obstruct the port for larger vessels to enter the same port.
- The charging and mooring mechanism should be able to operate in a temperature range of +35.5°C till -16.7°C.
- The charging and mooring mechanism should be able to withstand precipitation up to 153.8 mm/month
- The charging and mooring mechanism should be able to operate normal up to windforce 7 Bft
- The charging and mooring mechanism should be able to operate in restricted mode up to windforce 8 Bft. Restricted mode includes that the vessel should still be able to moor and charge, but the sailing schedule may be relaxed. Such that connection time and charging time can be extended
- The charging and mooring mechanism should be able to operate over a tidal difference of 7.1m.
- The charging and mooring mechanism should be protected from lightning strikes. The system might get damaged by the lightning, but may not create an arc flash.
- The charging and mooring mechanism should be protected to deal with splash water.

- The charging and mooring mechanism should be protected to deal with possible frost on the surface.
- The charging and mooring mechanism should be located such that is it protected from human interaction when the vessel is not in the port.
- The mooring mechanism should be installed on a location where the foundation is suitable to support the mooring forces.
- The charging and mooring should be able the handle the wave spectrum from the scatter plot below, covering the 98% likelihood

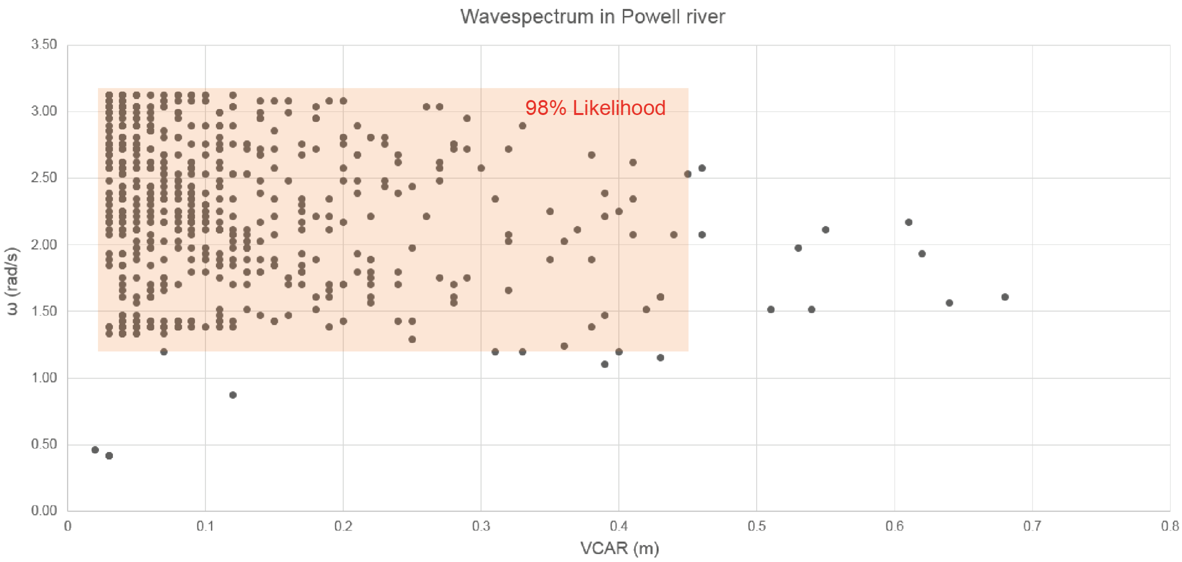


Figure B.2: The waves spectrum of the operational environment

B.1.2. Vessel design

- The charging and mooring mechanism should be located such that it does not cause an obstruction for vehicles and passengers moving on and of the ferry.
- The transport capacity of the vessel may not decrease due to the installation of the mooring and charging mechanism.
- The charging mechanism should be located in an area where personal and passengers are protected in the case of an arc flash.
- The mooring mechanism should be installed on the vessel where it is strong enough to support the mooring forces.

B.1.3. Ship motions

- The expected vessel motions are based on sea keeping simulations with the following input:
  - The vessel load is 1728 ton or 1611 ton
  - The wave spectrum in which it operates as described before.
  - Vessel speed is 0 kn.
  - The direction of the waves can vary with 360°.
  - The hull form will be equal as it is for the hybrid vessel.
- The charging mechanism should be able to deal with to following motions during charging, for location (x = 37.13, y = 4.531, z = 5.71). COG is at (0,0,0)
  - x ± 0.015 m

  - y ± 0.068 m
  - z ± 0.270 m

- The charging system should be able to connected while the vessel is moving with the motions described above.
- The charging system should be able to connect while the vessel is not perfectly aligned to the ramp with a deviation of ± 5° from the centerline.
- The mooring system should be able to moor the vessel when it is moving as described above.

B.2. Electrical aspects

B.2.1. Power demand

- The required charging power is based on the existing sailing schedule of the ferries.
- The required charging power is based on the vessel loading is described before in the operating environment and the loading in the ship motions.
- The required charging power is 4 MW, presenting the worst case scenario for route 25 and route 18.

B.2.2. Voltage level

- The LV option is 1000 VDC, 4000 A.
- The HV option is 6,6 VAC, 350 A.
- For the charger design the LV option is initially assumed, presenting the worst case scenario for the cable dimensions, due to the large current.
- The HV option may be analyzed and compared later in the research to show the predicted difference in cable behaviour.

B.2.3. Cable

- The maximum conductor size of the power cable should be in accordance with standard BV NR 467 Rules for the Classification of Steel Ships, Part C, Chp 2, Sec 3.'
- The cable conductor should have a maximum operation temperature of at least 90°C.
- The cable should be flame-retardant
- The cable should be protected to UV radiation
- The cable should be resistant to oil, sea-water and sea-air.
- The cable should only transfer power, no data communication or so is demanded.
- Possible cable configurations are provided in the table below. These are possible but not exclusive.

Connector

- The connector should be able to transfer 4MW.
- The connector should be able to operator on LV, 1000 VDC, 4000 A.
- The plug and socket-outlet arrangement shall be tted with a mechanical-securing device that locks the connection in the engaged position.
- The plugs and socket outlets shall be designed so that an incorrect connection cannot be made.
- Socket-outlets and inlets shall be interlocked with the earth switch so that plugs or connectors cannot be inserted or withdrawn without the earthing switch in the closed position.
- Handling of plug and socket outlets shall be possible only when the associated earthing switch is closed.

- Plugs shall be designed so that no strain is transmitted to the terminals and contacts. The contacts shall only be subjected to the mechanical load which is necessary to provide satisfactory contact pressure, including when connecting and disconnecting.
- Each plug shall be tted with pilot contacts for continuity verication of the safety circuit. For single plug connections, a minimum of three pilots are required. If more than one cable is installed an interlocking shall be used so that no cable remains unused.
- Support arrangements are required so that the weight of connected cable is not borne by any plug or socket termination or connection.
- In the case of a new designed plug, it should be tested and approved according to IEC 62613-1.

B.2.4. Automation

- The charging mechanism should be automated.
- The mooring mechanism may be either automated or manual controlled.
- In the case of a manual controlled mooring mechanism, the operation force may not exceed 100N.

B.2.5. Connection time

- The maximum connection time for the charging mechanism and the mooring mechanism is 30 sec.
- The maximum disconnection time for the charging and mooring mechanism is 30 sec.
- The connection of the charging mechanism may start after the mooring mechanism is connected.
- The disconnection of the mooring mechanism may start after the charging mechanism is disconnected.

B.2.6. Safety

Electric safety during normal operation

- The system should be protected from passengers and staff while charging.
- The system should be protected from passengers and staff when is resting state, so when the vessel is sailing.
- Passengers and staff should be protected form the inductive field around the charge in the case that this is induced.
- Ferry staff should have completed sufficient training for operation of the charger, for the defined power level. This is required even if the charger operation is automated.
- The plug-socket connection should be protected from the environmental conditions during charging.
- The plug and socket connector should be protected form the environmental conditions when it is in resting state.

Electric safety in case of failure

- Passenger, staff, vehicles and the surrounding environment should be protected for the occurrence of an arc flash.
- The charging and mooring mechanism should be the weakest link in the case of electric failure. Only the mechanism itself should be damaged, not the vessel or port infrastructure
- Sufficient fire fighting equipment should be available near the charging mechanism.

Mechanical safety during normal operation

- The charging and mooring mechanism should be protected from passengers and vehicles when the vessel is docked and charging.

- The charging and mooring mechanism should be protected from passengers and vehicles when the mechanisms are in resting state. Mechanical safety in case of failure
- Passengers, staff, vehicles and the environment should be protected in the case of mechanical failure of the charging and/or mooring mechanism.
- The charging and mooring mechanism should be the weakest link. Only the mechanism may get mechanically damaged, not the vessel or the port infrastructure.

Sufficient testing before installation

- In the case a new charging and/or mooring mechanism is developed, sufficient factory testing should be performed to ensure the required safety and performance
- General testing of the charging installation should be executed according to IEC 80005.
- Testing of the plug-socket connection should be executed according to IEC 62613.
- Testing of the power cable should be executed according to IEC 60502.

Sufficient testing and maintenance during lifetime

- During the life time of the system, sufficient maintenance should be executed to the mechanical and electrical properties of the system, to continuously ensure sufficient safety and performance.
- The charging mechanism should be tested according to IEC80005.
- The plug-socket connection should be tested according to IEC62613.
- The power cable of the charging mechanism should be tested according to IEC 60502.

B.2.7. Costs

- No explicit cost requirement have been provided by BC Ferries or Damen.

B.2.8. Performance and durability

Mechanical construction

- The construction of the charging and mooring mechanism should be able to withstand all forces caused by the environmental conditions.
- The construction of the charging and mooring mechanism should be able the withstand all forces exerted on it, due to the connection to the vessel.
- The mechanical construction should be design to withstand cyclic loading's, which can cause fatigue.
- The mechanism construction should be designed modular, such that failing parts can be replaced easily.
- Constructional parts should be standardized, when possible. Such that these can quickly be replaced when failure occurs.

Mechanical material properties

- The parts used for the construction should be resistant to water.
- The parts used for the construction should be flame resistant.
- The parts used for the construction should be UV-resistant.
- The parts used for the construction may not be damaged by frost.
- The yield strength of the parts used for the construction should be sufficient to handle the forces exerted on the system.

Charger power system

- The power supply of the charger may not easily be disrupted due to movements of the vessel. power supply of the charger may not easily be disrupted by forces exerted of the charging mechanism cause be the environmental conditions. power supply of the charger may not easily be disrupted by moisture.

Control system hardware

- The control system of the charging and mooring mechanism, should be constructed out of components which are well protected to the environmental conditions.
- The quality of sensor signals may be affected by moisture of light effects.
- The control system should be designed such that component are easy reach and replace in the case of failure.
- The hardware incorporated in the control system should be standardized such that these can quickly be replaced in the case of failure.

Control system software

- The control system should be programmed robust, should that is it not affected by external disturbances or noise.

B.2.9. Addition operator requirements

- All vessels should be interchangeable over the ferry lines.

C

Seakeeping calculation

C.1. RAOs, Load case 1

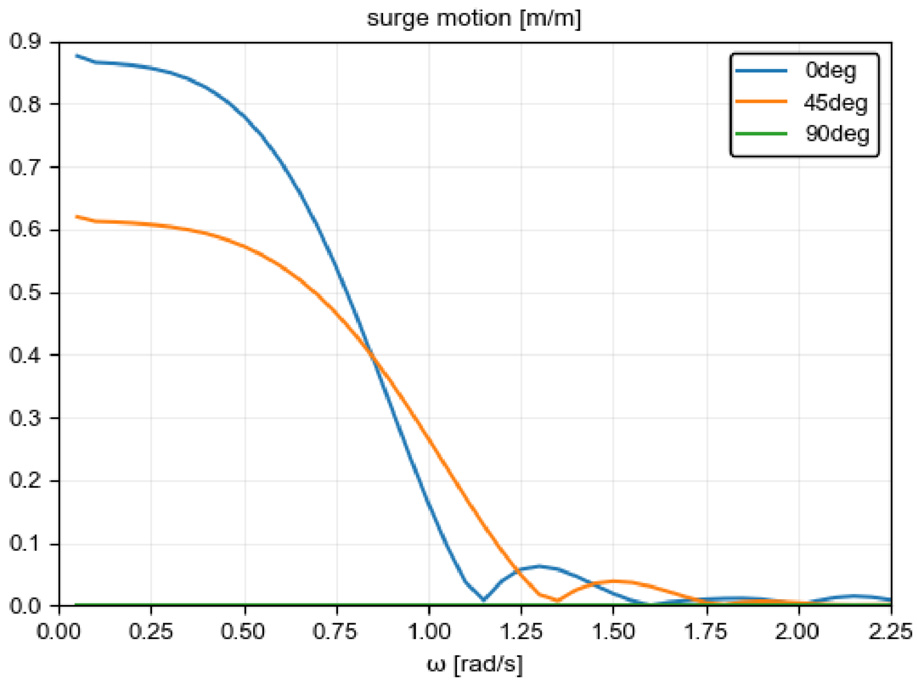


Figure C.1: RAO of surge motion at the COG.

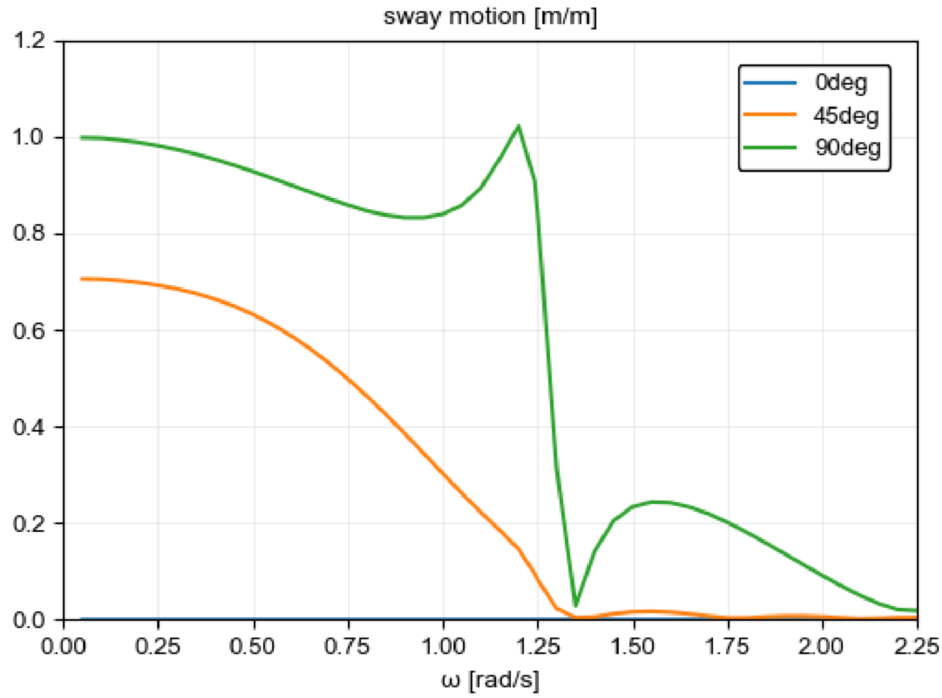


Figure C.2: RAO of sway motion at the COG.

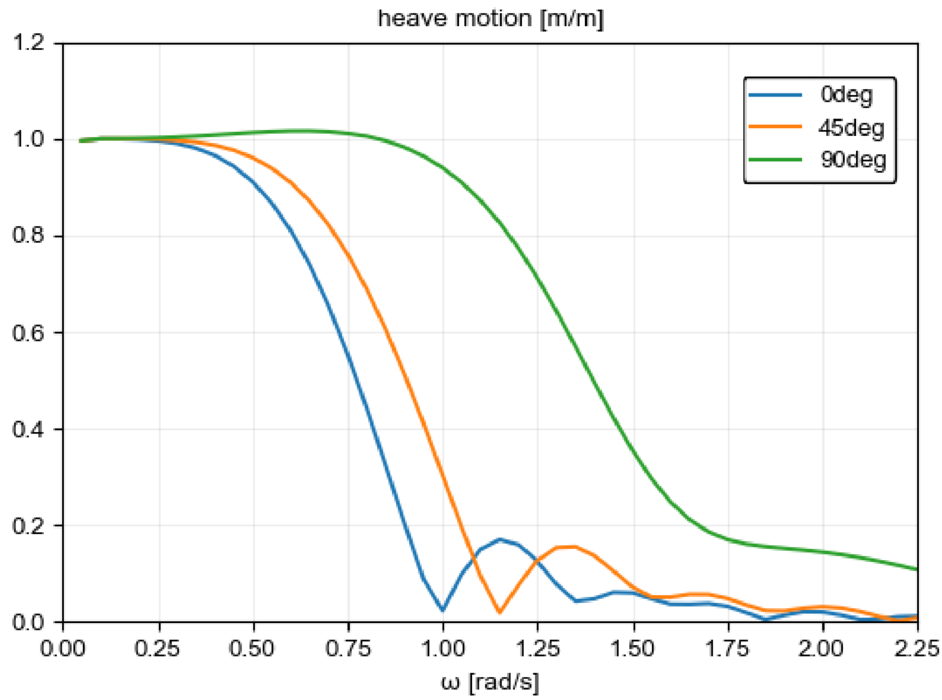


Figure C.3: RAO of heave motion at the COG.

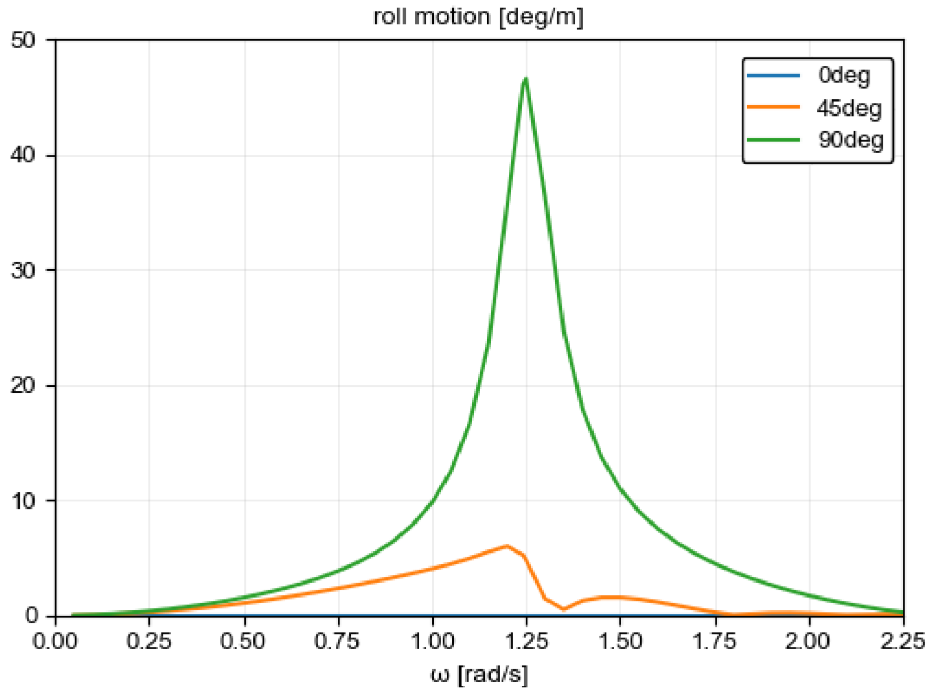


Figure C.4: RAO of roll motion at the COG.

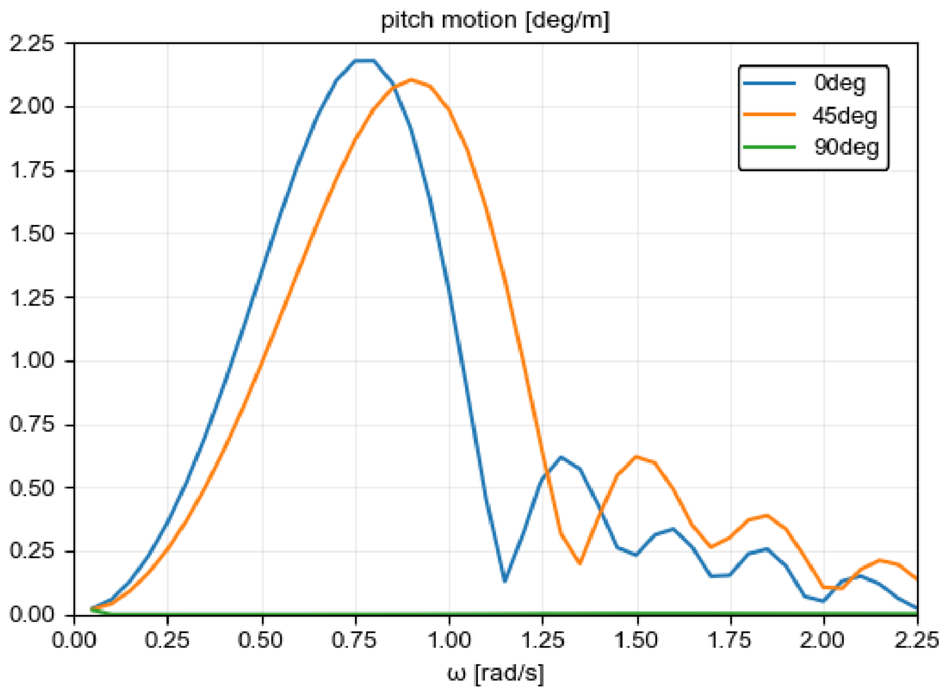


Figure C.5: RAO of pitch motion at the COG.

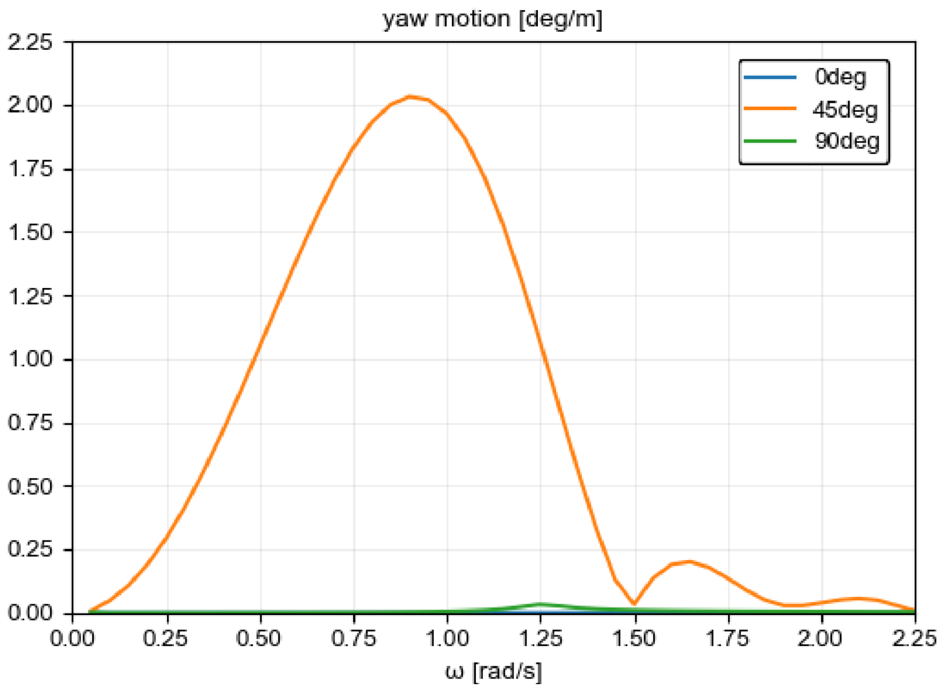


Figure C.6: RAO of yaw motion at the COG.

C.2. RAOs, Load case 2

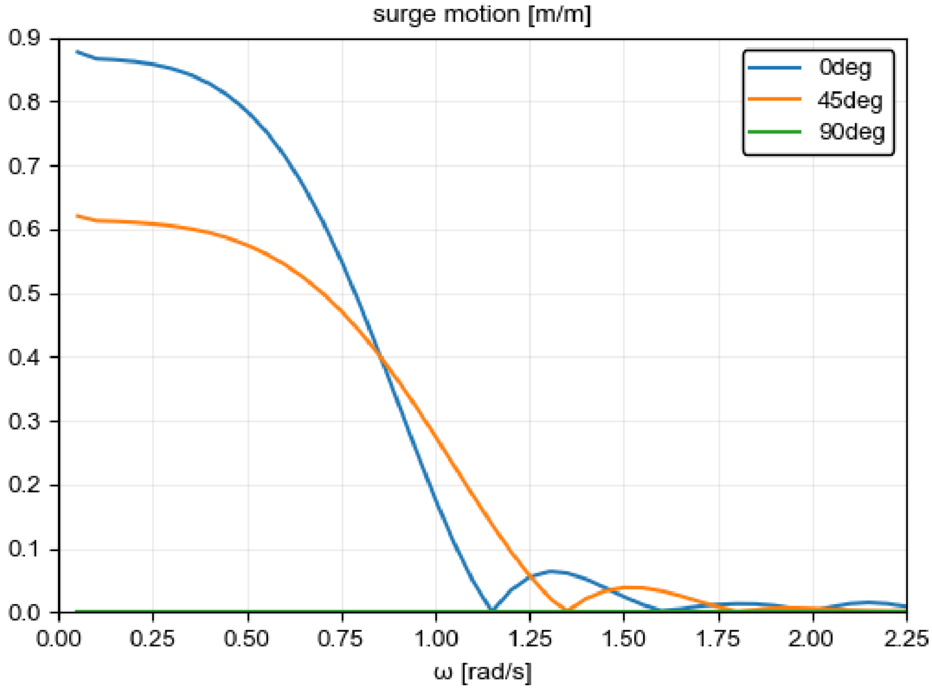


Figure C.7: RAO of surge motion at the COG.

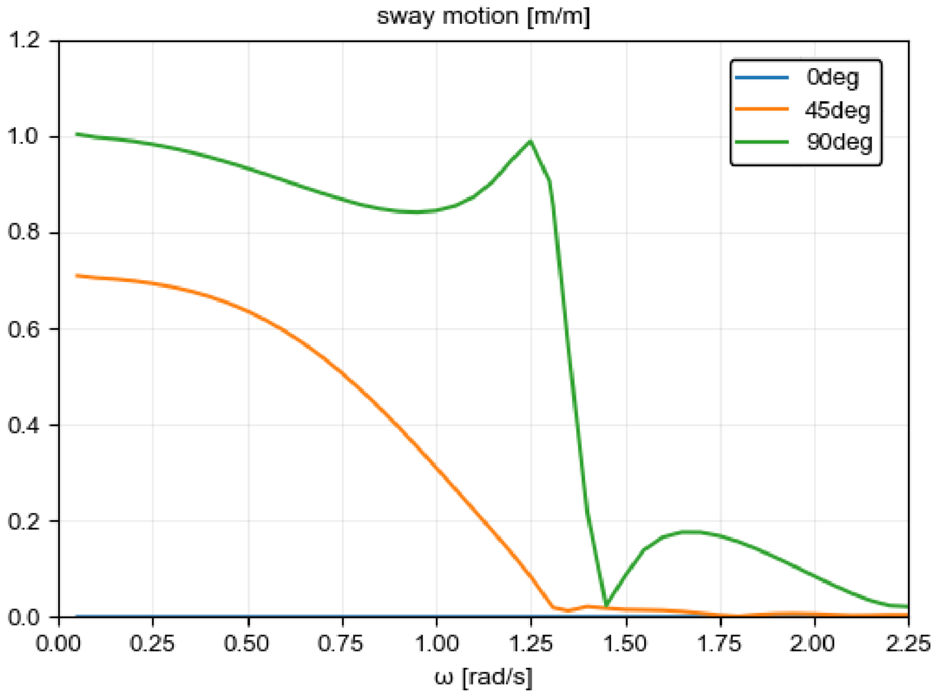


Figure C.8: RAO of sway motion at the COG.

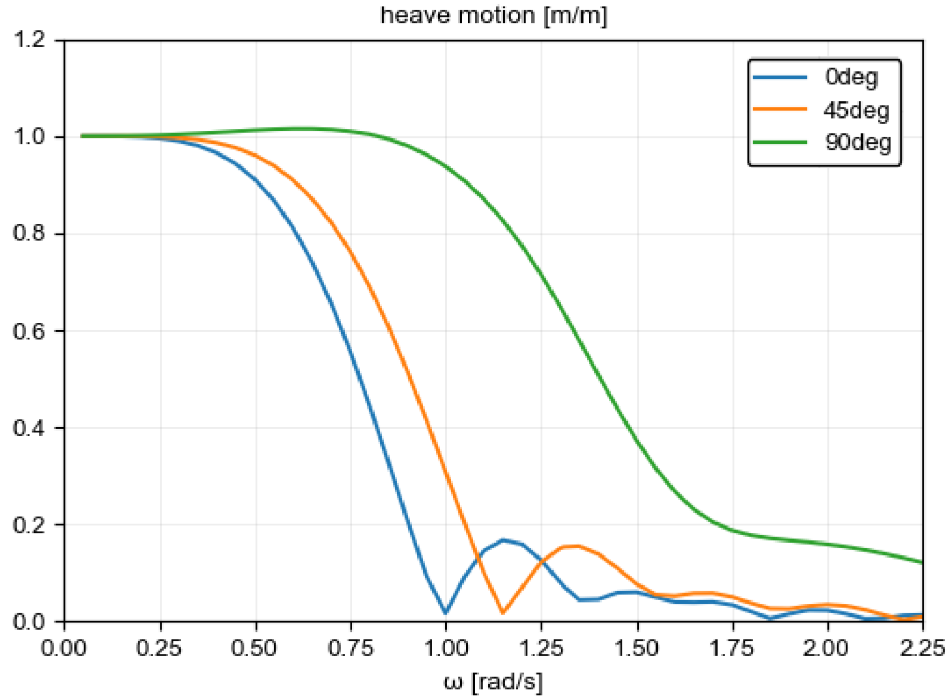


Figure C.9: RAO of heave motion at the COG.

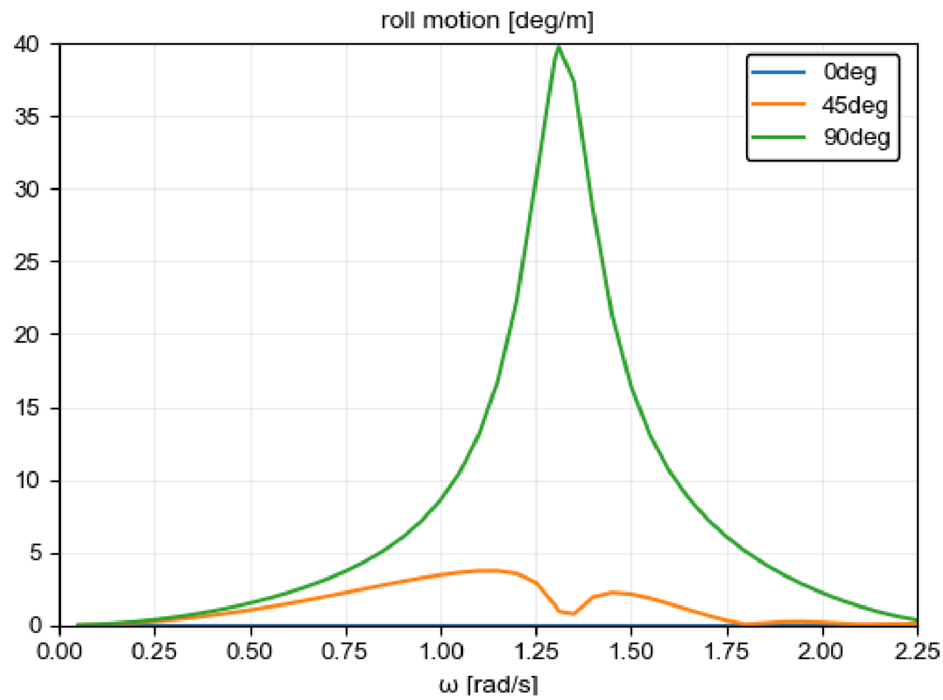


Figure C.10: RAO of roll motion at the COG.

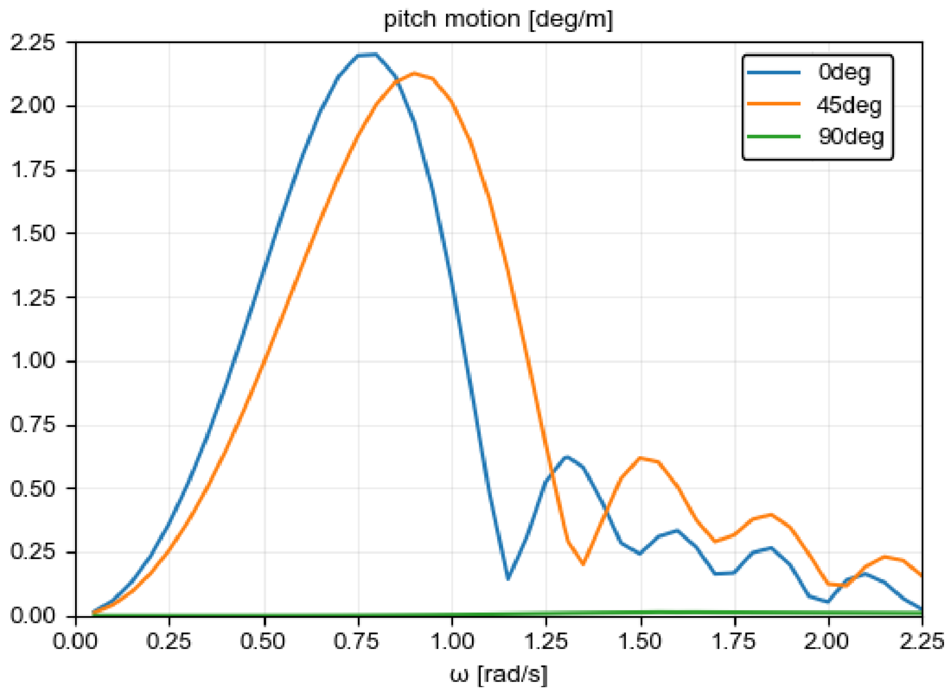


Figure C.11: RAO of pitch motion at the COG.

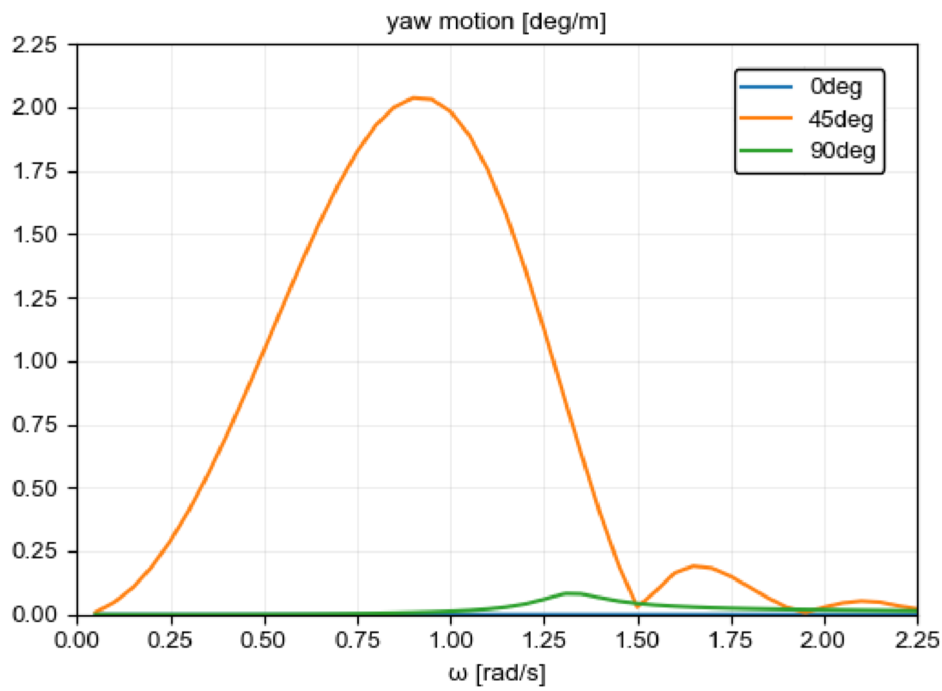


Figure C.12: RAO of yaw motion at the COG.

C.3. RMS motions of bolder, Load case 2

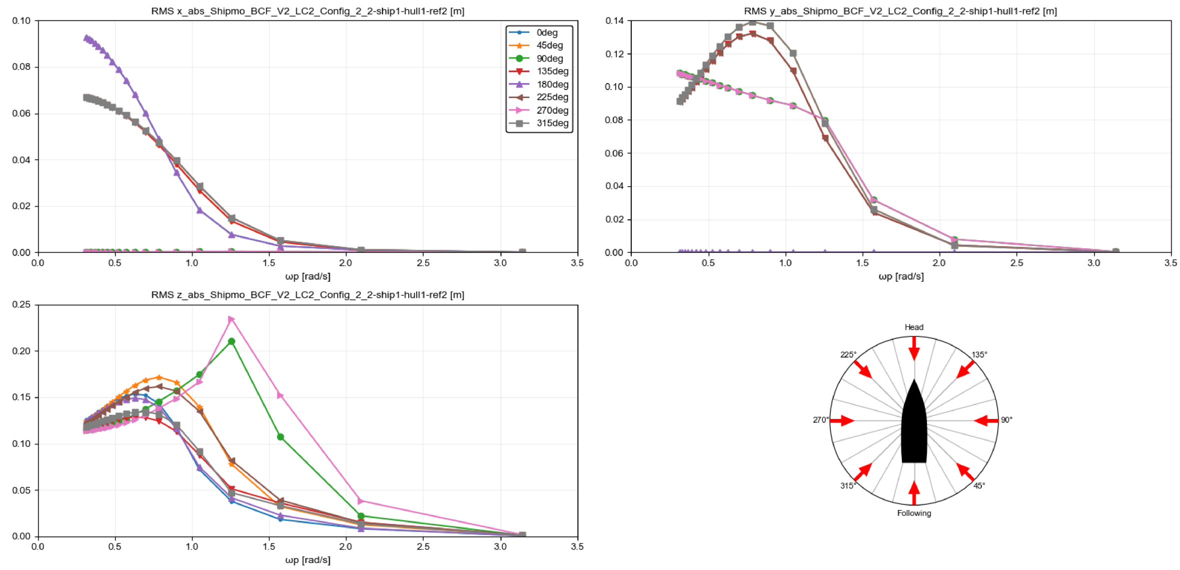
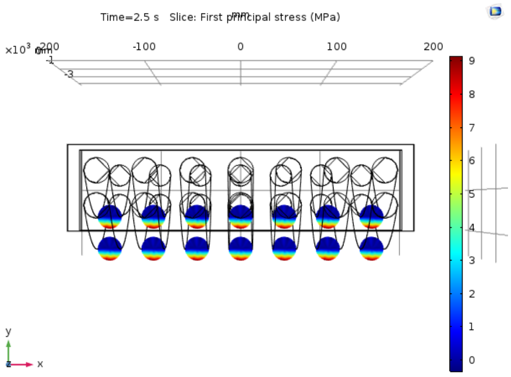


Figure C.13: The RMS of the bolder motions for load case 2.

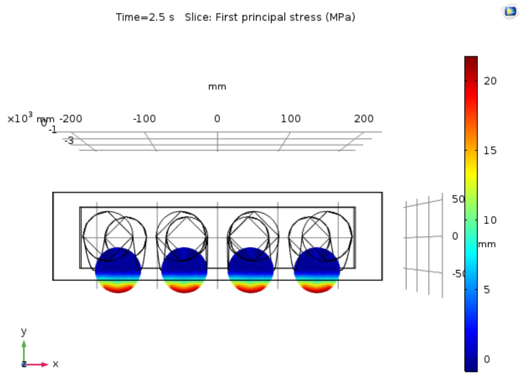
D
Cable simulation

D.1. Motion pattern 1

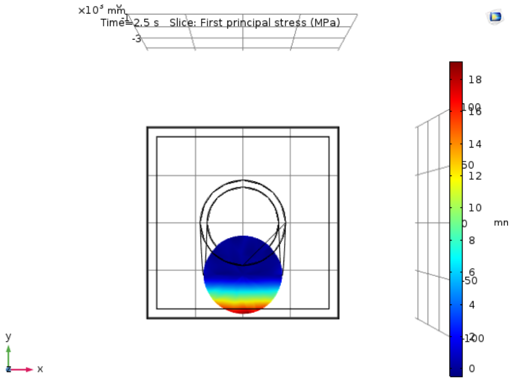
D.1.1. High tide, 3m cable length.



(a) Configuration 1

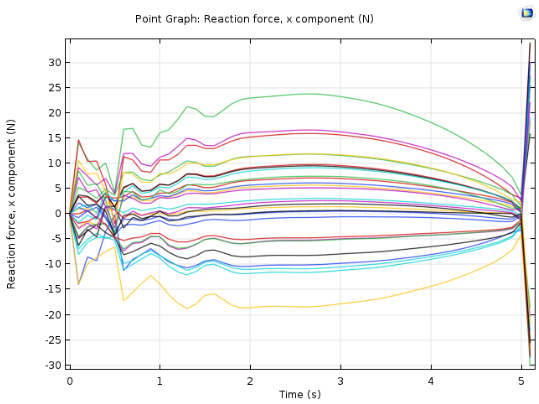


(b) Configuration 2

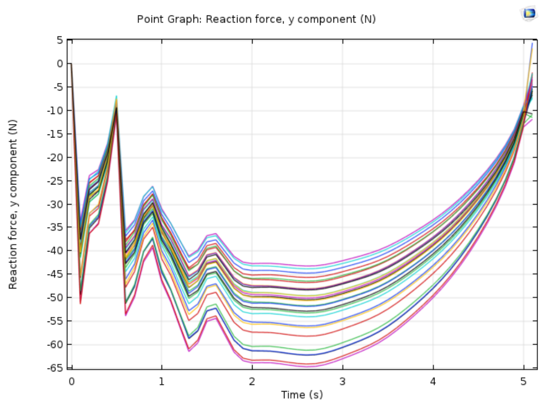


(c) Configuration 3

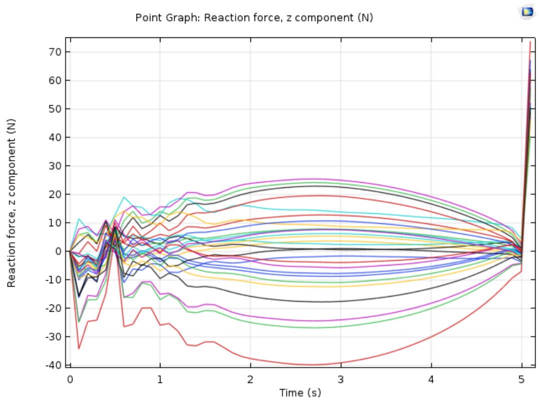
Figure D.1: Section view of the principal stress profile at the the halfway length of the cable at t=2.5.



(a) Resultant force in x direction

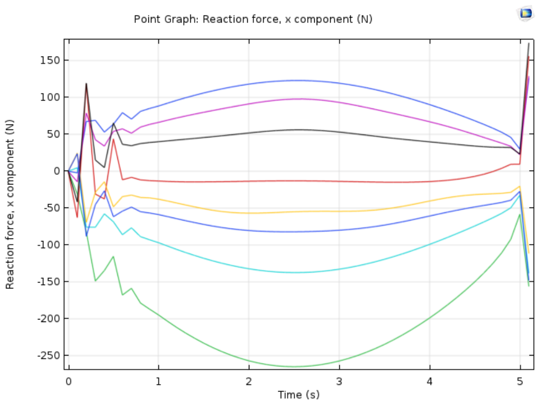


(b) Resultant force in y direction

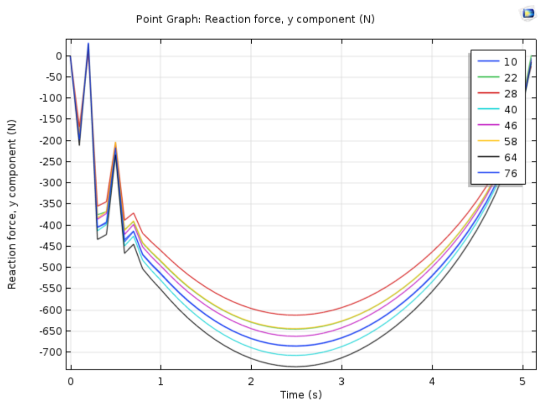


(c) Resultant force in z direction

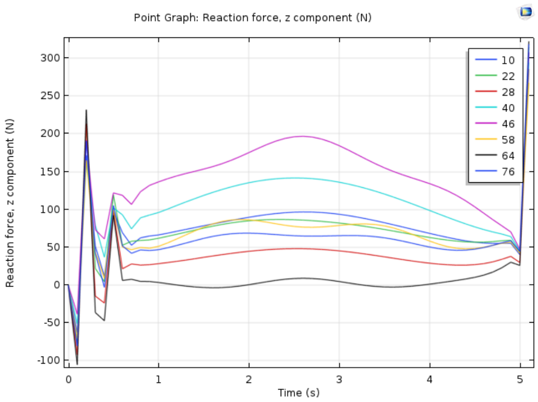
Figure D.2: The resultant forces of the plug on the cable connection points for configuration 1, subjected to motion pattern 1 in the high tide situation. Plot for one period of the motion.



(a) Resultant force in x direction

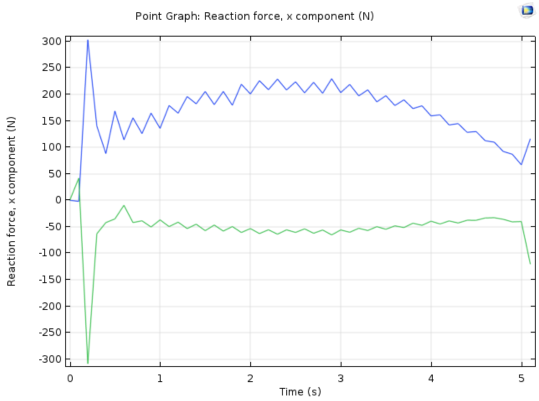


(b) Resultant force in y direction

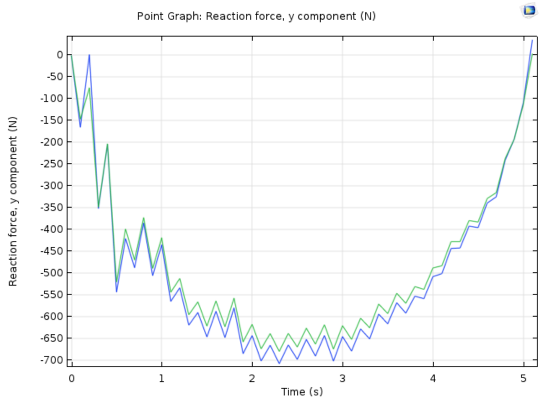


(c) Resultant force in z direction

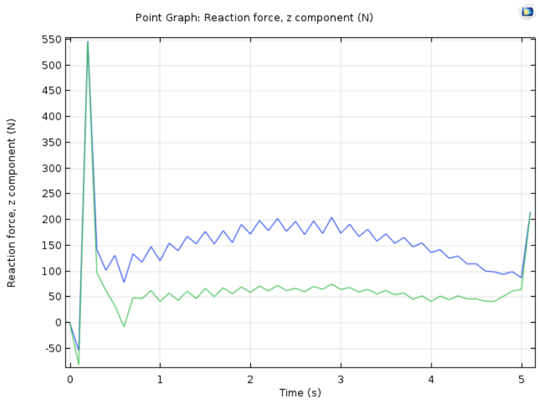
Figure D.3: The resultant forces of the plug on the cable connection points for configuration 2, subjected to motion pattern 1 in the high tide situation. Plot for one period of the motion.



(a) Resultant force in x direction



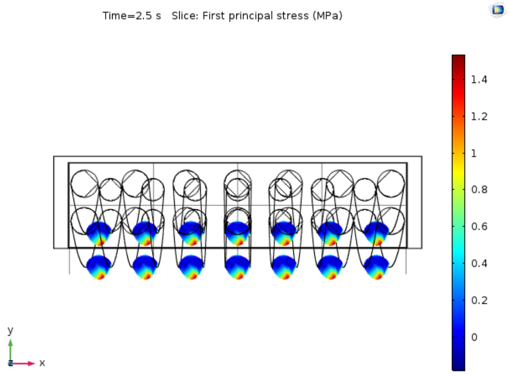
(b) Resultant force in y direction



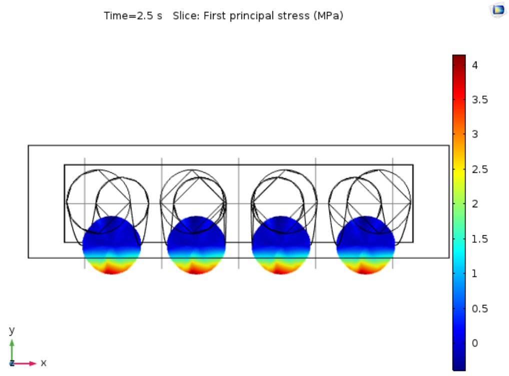
(c) Resultant force in z direction

Figure D.4: The resultant forces of the plug on the cable connection points for configuration 3, subjected to motion pattern 1 in the high tide situation. Plot for one period of the motion.

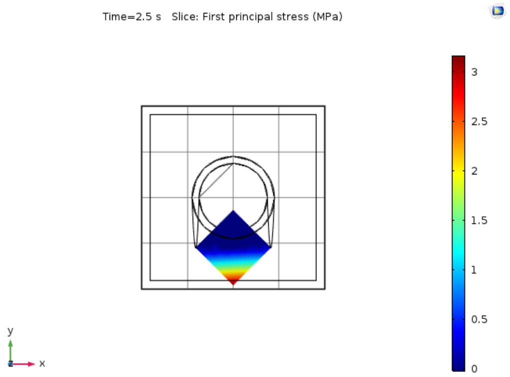
D.1.2. Low tide, 10m cable length.



(a) Configuration 1

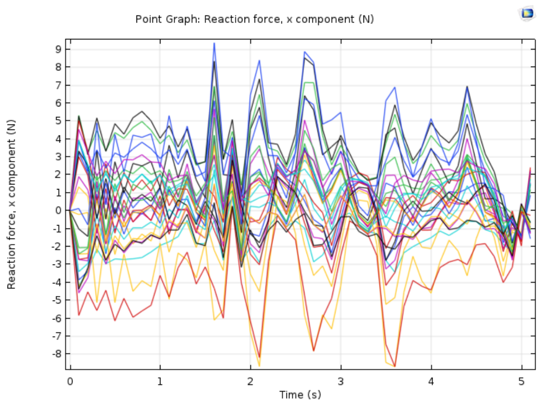


(b) Configuration 2

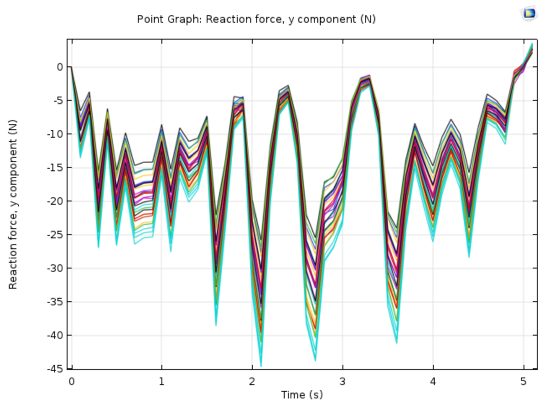


(c) Configuration 3

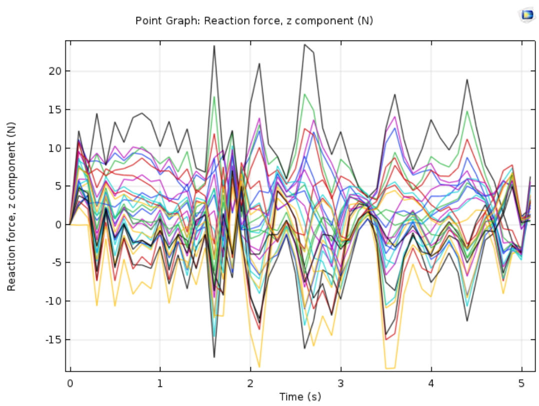
Figure D.5: Section view of the principal stress profile at the the halfway length of the cable at t=2.5.



(a) Resultant force in x direction

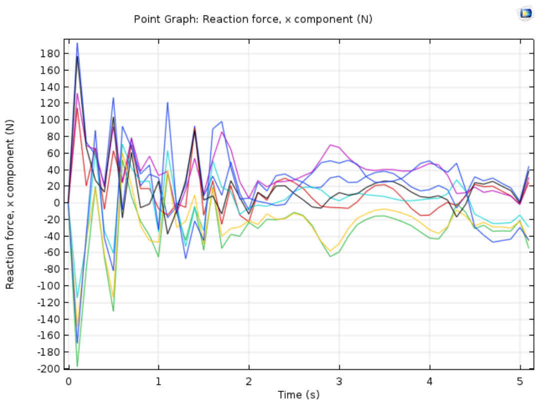


(b) Resultant force in y direction

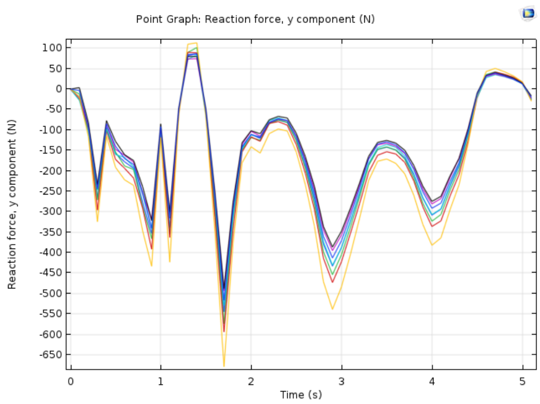


(c) Resultant force in z direction

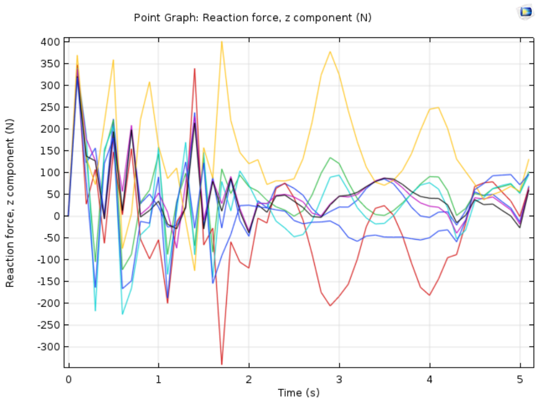
Figure D.6: The resultant forces of the plug on the cable connection points for configuration 1, subjected to motion pattern 1 in the low tide situation. Plot for one period of the motion.



(a) Resultant force in x direction

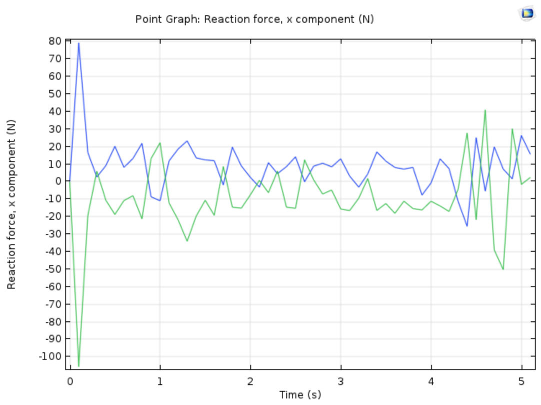


(b) Resultant force in y direction

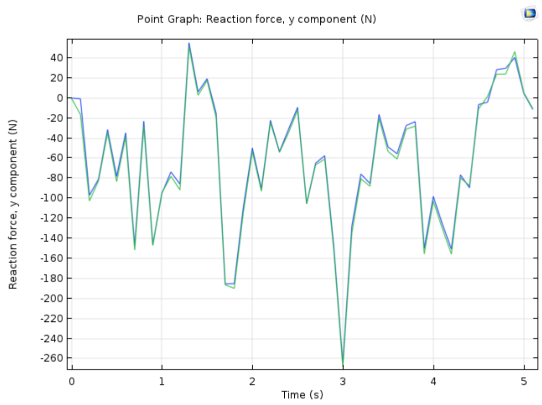


(c) Resultant force in z direction

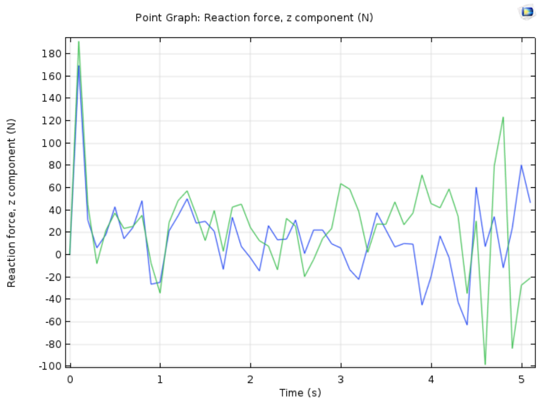
Figure D.7: The resultant forces of the plug on the cable connection points for configuration 2, subjected to motion pattern 1 in the low tide situation. Plot for one period of the motion.



(a) Resultant force in x direction



(b) Resultant force in y direction

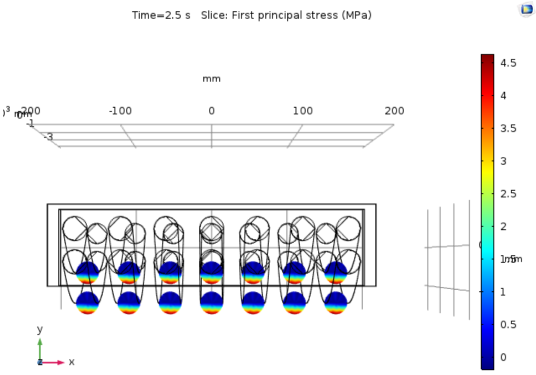


(c) Resultant force in z direction

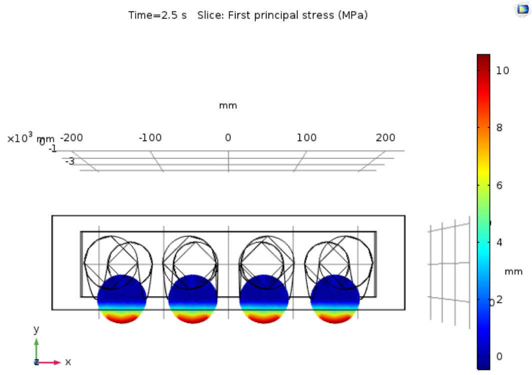
Figure D.8: The resultant forces of the plug on the cable connection points for configuration 3, subjected to motion pattern 1 in the low tide situation. Plot for one period of the motion.

D.2. Motion pattern 2

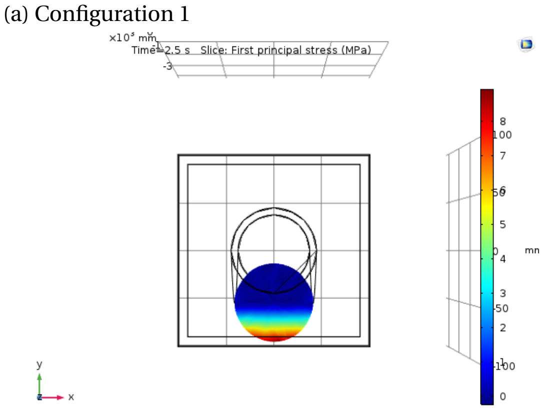
D.2.1. High tide, 3m cable length.



(a) Configuration 1

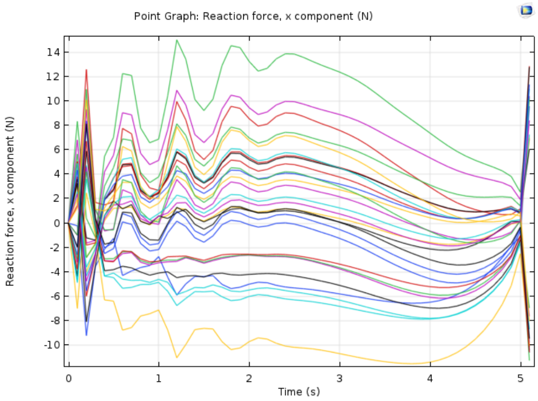


(b) Configuration 2

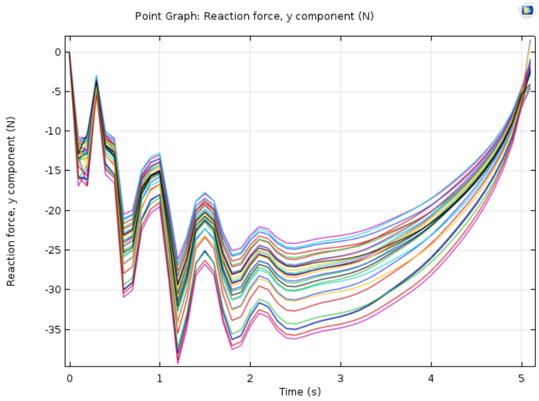


(c) Configuration 3

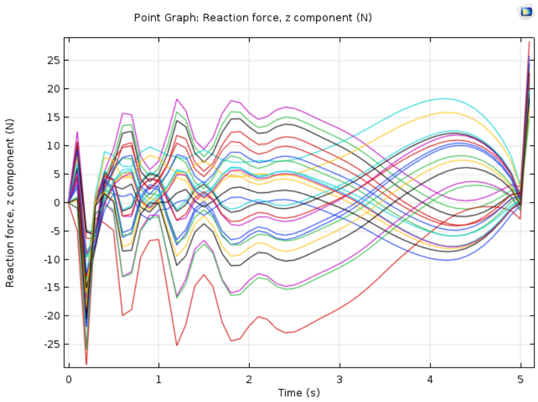
Figure D.9: Section view of the principal stress profile at the the halfway length of the cable at t=2.5.



(a) Resultant force in x direction

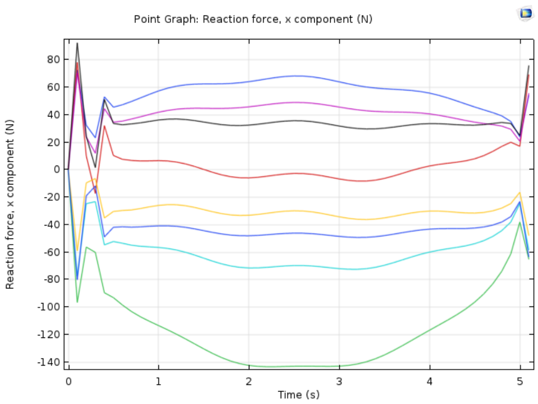


(b) Resultant force in y direction

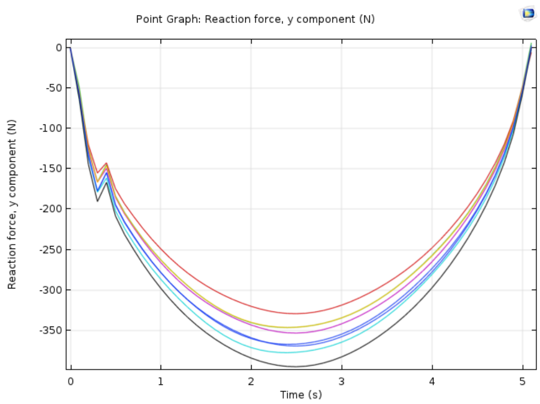


(c) Resultant force in z direction

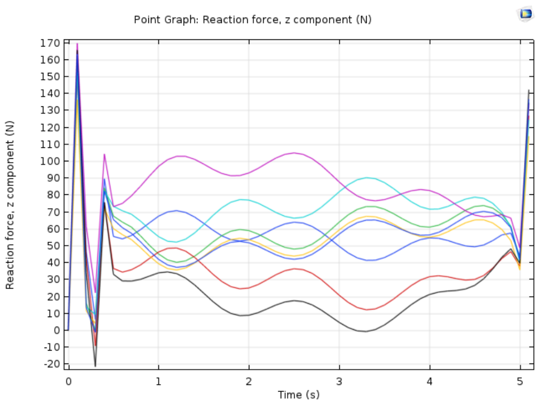
Figure D.10: The resultant forces of the plug on the cable connection points for configuration 1, subjected to motion pattern 2 in the high tide situation. Plot for one period of the motion.



(a) Resultant force in x direction

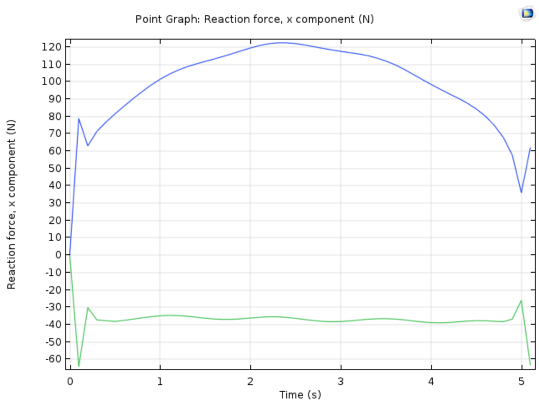


(b) Resultant force in y direction

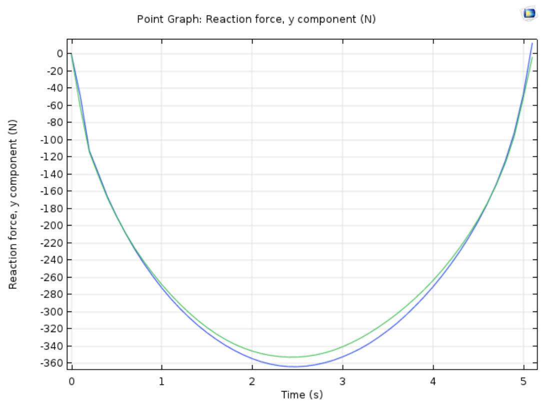


(c) Resultant force in z direction

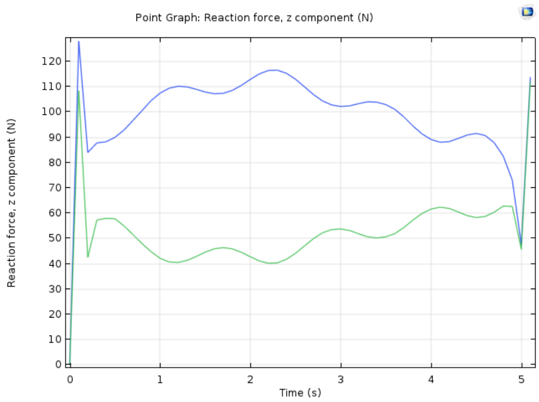
Figure D.11: The resultant forces of the plug on the cable connection points for configuration 2, subjected to motion pattern 2 in the high tide situation. Plot for one period of the motion.



(a) Resultant force in x direction



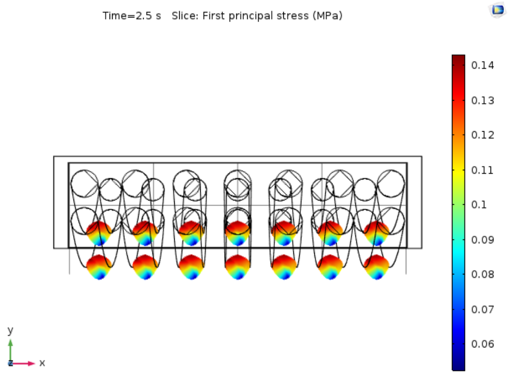
(b) Resultant force in y direction



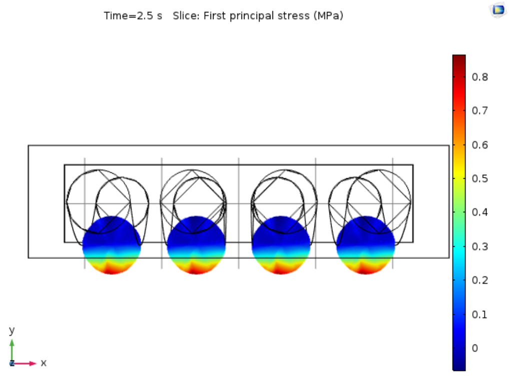
(c) Resultant force in z direction

Figure D.12: The resultant forces of the plug on the cable connection points for configuration 3, subjected to motion pattern 2 in the high tide situation. Plot for one period of the motion.

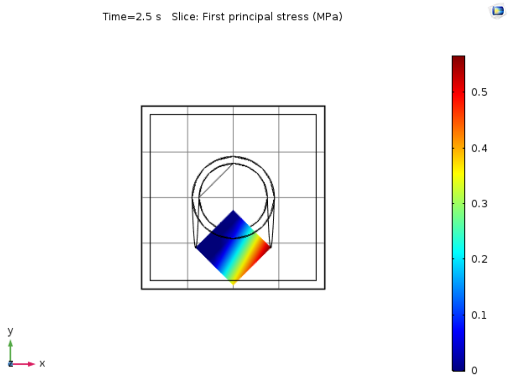
D.2.2. Low tide, 10m cable length.



(a) Configuration 1

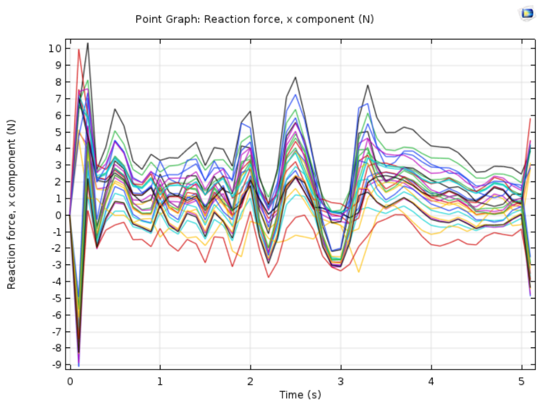


(b) Configuration 2

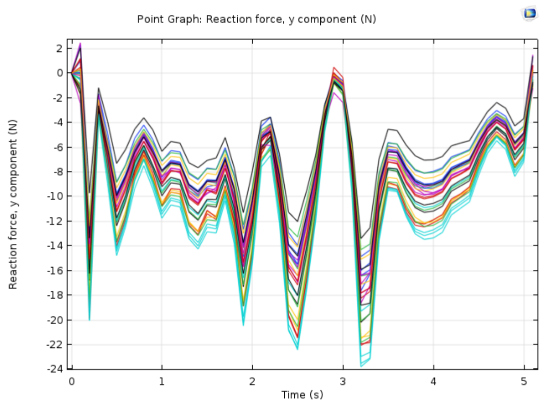


(c) Configuration 3

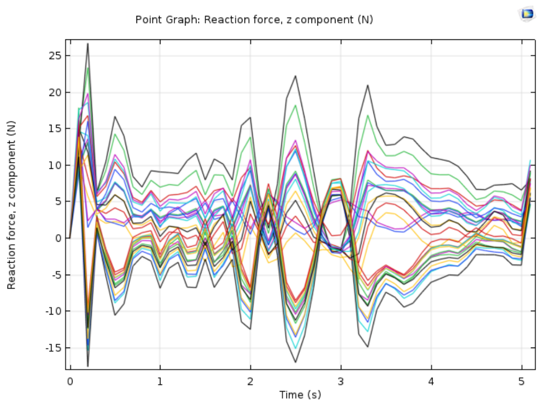
Figure D.13: Section view of the principal stress profile at the the halfway length of the cable at t=2.5.



(a) Resultant force in x direction

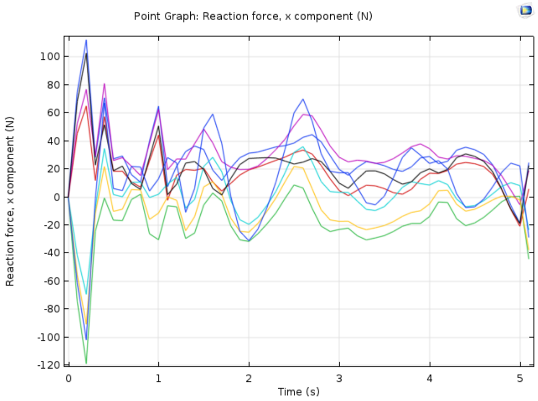


(b) Resultant force in y direction

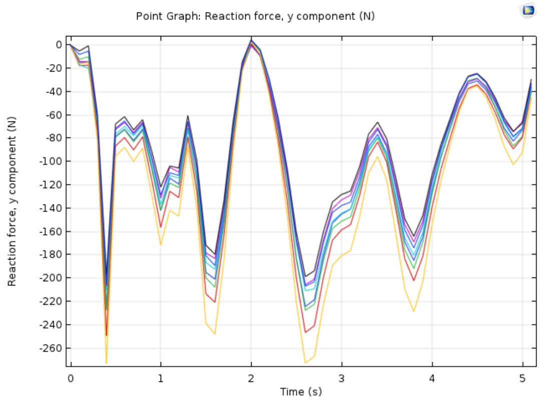


(c) Resultant force in z direction

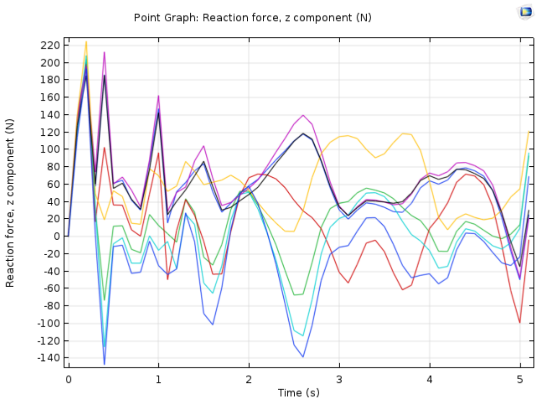
Figure D.14: The resultant forces of the plug on the cable connection points for configuration 1, subjected to motion pattern 2 in the low tide situation. Plot for one period of the motion.



(a) Resultant force in x direction

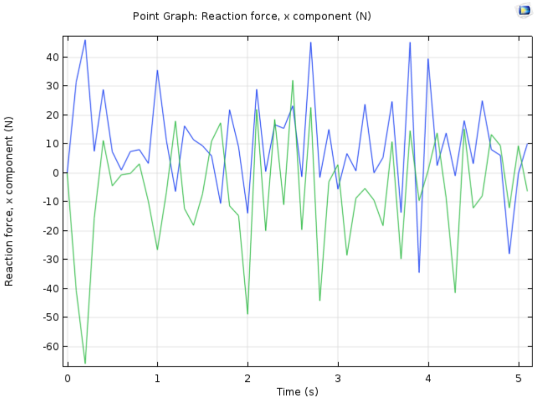


(b) Resultant force in y direction

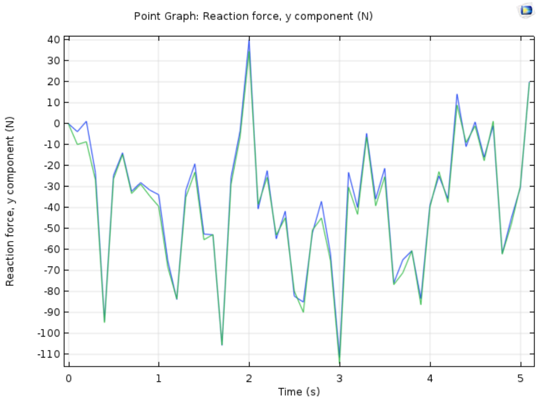


(c) Resultant force in z direction

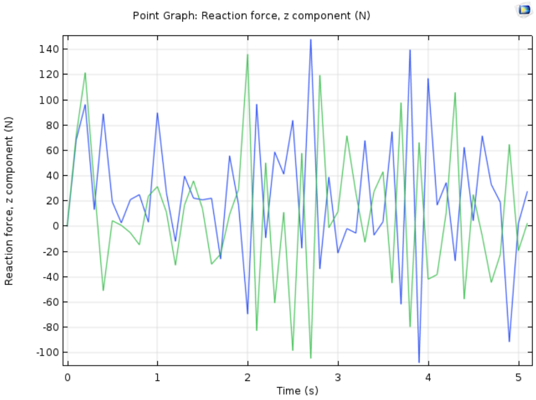
Figure D.15: The resultant forces of the plug on the cable connection points for configuration 2, subjected to motion pattern 2 in the low tide situation. Plot for one period of the motion.



(a) Resultant force in x direction



(b) Resultant force in y direction



(c) Resultant force in z direction

Figure D.16: The resultant forces of the plug on the cable connection points for configuration 3, subjected to motion pattern 2 in the low tide situation. Plot for one period of the motion.

E

Paper

The development of a guideline on how to select a charging and mooring mechanism for an electric vessel

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Abstract

Due to the global climate change there is a increasing demand for transportation on renewable fuels. An increasing trend in electric propulsion can already be seen in the automotive industry and this is now also gaining popularity in the maritime sector. An electric vessel generally requires a charging and a mooring system to operate as desired. Various systems have been developed already. However, these are no standardized solutions but all one of a kind systems designed for a specific vessel or fleet. Which of these is the best solution strongly depends on the vessel characteristics and the operating environment. To supply the expected increasing demand for electric vessels, a guideline is developed which will help the engineer to find a suitable charging and mooring mechanism and the decrease the selection time for this system. This guideline is developed based on the knowledge gained by a case study for a vehicle ferry. The guideline provides insight in the influential factors while selecting an mechanism and an overview of the currently existing systems. The guideline is validated while selecting a charging mechanism for an electric tug.

1. Introduction

The majority of the vessels all over the world are sailing on fossil fuels such as heavy fuel oil or diesel. When burning these fuels for the vessel propulsion, greenhouse gasses such as carbon-dioxide are emitted into the atmosphere which cause the world wide climate change. To limit the climate change consequences, the use of renewable energy resources is gaining popularity. Electric propulsion is one of the solutions and shows an increasing demand in the automotive industry for the last eight years (Agency, 2018). In 2015 the first full electric ferry was launched in Norway and since than a hand full of electric vessels has been developed by various shipyards. These concern mainly ferries since these sail only short distances and therefore the required onboard energy is limited. Of course, this is only the case as long as it can charge again at its destination. Within Damen multiple projects are ongoing which involve the development of an electric vessel. One of these concerns an 81m long ferry, designed to transport vehicles and passengers over multiple routes around Vancouver and Vancouver Island. This ferry will initially be sailing in hybrid mode but it should be converted into an electric ferry later on. To enable this ferry to sail on electricity, a charging system should be installed in the port. The ferries that are currently sailing on these route do not moor during the transshipment of passengers and vehicles, but it is continuously sailing towards the quay. To limit the required energy form the charging mechanism, a mooring mechanism for the ferry is required, such that the propeller can be turned off while the vessel is in the port. Limiting the energy consumption limits the energy costs and required size of the charging station.

Due to the trend seen before in the automotive industry and the recent projects announced, it is expected that the demand for electric vessels will increase within the near future (Group, 2018a), (Group, 2018b), (ASA, 2018). To ease the development of these vessels, the goal of this research is to develop a guideline on how to select a charging and mooring mechanism for an electric vessel. This guideline should decrease the selection time for finding a charging and/or mooring mechanism and such the time required for the complete development of the vessel is decreased. This will provide Damen a strategic advantage over other shipyards, since vessels can be delivered earlier and the production costs are decreased since less research is needed.

1.1. Research approach

The development of the guideline is approached as follows. First a generic engineering design method is chosen from literature. The chosen method is from Cross (2000), which is schematically shown in figure 1.

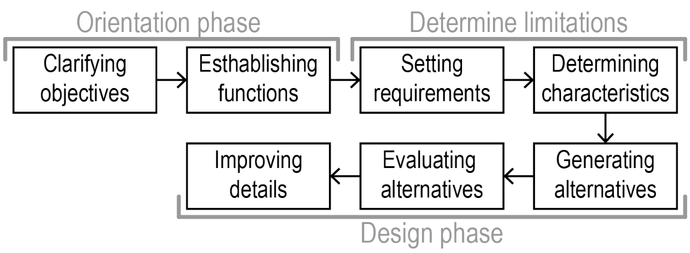

Figure 1: The engineering design method from (Cross, 2000).

This method is applied in a case study to design a charging and mooring mechanism for the BC Ferries case. The procedure of the case study is evaluated afterwards and the knowledge gained in this process is used to construct the guideline. The guideline will be validated while selecting a charging mechanism for an electric tug. Before the case study, first a state of the art research is executed to gain knowledge into the current charging technologies and the mechanisms that have been developed already.

2. State of the art

In subsection 2.1 a literature study is executed to the possible technologies that can be used to transfer electric energy. Afterwards it is investigated what kind of charging and mooring mechanisms are currently available in 2.2.

2.1. Literature research on charging technologies

To charge the onboard battery, electric energy should be transferred from the shore grid to the vessel. Various technologies are available to do so, of which some are more common than others. The most ordinary way of transferring electric energy is by conduction, which transfers electrons through a metal from the source to the battery. For this charging technology metal-to-metal contact is required between the shore and the ship. Multiple wireless charging technologies have been developed as well, of which inductive charging is the most established one. Other wireless charging options are using infrared, radio frequency or ultrasound to transfer the electric energy. These are not commonly used but are currently in development, mainly for charging purposes of smaller devices such as mobile phones.

Radio frequency charging does not seem feasible for vessel charging. To transfer a relative high power by radio frequency, a high dBm should be emitted. This would block all other radio frequency signals used, and such, disable the mobile phone communication, radio broadcasts, etc. Also ultrasound is not feasible for vessel charging purposes. The efficiency of this technology is generally only 10-20% when transmitted through water (Mazzilli et al., 2010). Transmission through air would result in an even lower efficiency. The amount of power that should be transferred will cause a great cyclic pressure on the vessel hull, damaging the vessel. Infrared charging is rejected as well, due to is low charging efficiency which is generally between 4-20% (Dubay et al., 2013). For the continuation of this research only conductive and inductive charging will be considered as possible charging technologies.

2.2. Currently existing mechanisms

Both for charging and mooring of electric vessels, various systems have been developed. The developments on these technologies are discussed in this section, as well as the limitations that are observed for these systems.

2.2.1. Charging mechanisms

The existing charging mechanisms can generally be divided in six categories. These categories and their characteristics are provided below.

- Extendible arm. An arm with the plug is extended from the shore charging station, into the onboard socket connection. The arm is extended in only one direction and the range of motions in other directions is limited. The arm automatically connects, controlled by optical sensors.

- Robot arm. This arm is consist of two main beams and the plug secured at the hand position. The shoulder, elbow and wrist connection are all ball joints, allowing the system to move in all six degrees of freedom. The arm automatically connects, controlled by optical sensors.

- Automated crane. The plug is hanging on the crane, with the onboard socket aligned with the plug underneath. By gravity, the plug is lowered into the socket connection.

- Manual crane. A plug is hanging on power cables attached to the crane. This crane can generally be remote controlled to rotate the crane and vertically move the plug, such that the plug comes near the socket. From this point the plug should be secured manually into the socket.

- Inductive chargers. One coil is installed on the shore side and a second coil is mounted into the vessel side. Once the vessel arrives in the port, the area of the two coils will overlap and charging starts automatically.

- Battery replacement. The vessel batteries will not be charged on board in this case, but are taken out and replaced by charged batteries. The empty batteries are charged on shore.

The introduction of electric vessels and charging mechanism is has only started some years ago. There is not such thing as a standardized solution. The type of charging mechanism is typically varying for each electric vessel or fleet that is currently in operation. Since all chargers are also the first ones installed, is it rather logical that these have some malfunctions. The main issues observed are:

– The ability of the charger to deal with misalignments between the vessel and the shore.

– The ability of the charger to deal with the motions of the vessel caused by waves or moving vehicles.

– Power cable damages due to continuous movements caused by vessel motions and maneuver of plug to align with socket.

– Connecting issues due to external disturbances such as rain or sunlight.

2.2.2. Mooring mechanisms

The mooring technologies are divided in four categories. These are described below as well as their main characteristics.

- (semi) Manual mooring. The most common way of mooring vessels, is by mooring lines secured between onboard bolders and capstans on the shore. Semi automated systems, such as rotating winches, have been developed to automatically put tension on the mooring lines once these have been secured on the winch. Another semi automated solution is a quick release hook, easily releasing the mooring line.

- Vacuum mooring system. A suction cup is mounted on shore and sucks itself onto the vessel once these two touch. Multiple systems can be placed parallel to each other to increase the holding force.

- Magnetic mooring system. A magnet is mounted on shore and connects to the metal vessel hull once these two touch. Multiple systems can be placed parallel to each other to increase the holding force.

- Mechanical mooring system. Various automated mechanical systems have been developed, which basically secures one solid structure in or onto another. This includes for example an on shore beam with a ring moving over an onboard pin.

Automated mooring mechanisms have been used for a longer time already compared to the charging mechanisms. The vacuum mooring system from Cavotec for example, was already introduced in 1999 (Cavotec, 2018). The operational reliability of mooring mechanisms in general ifs higher compared to the charging mechanisms. However, these systems do have quite some limitations. All vacuum and magnetic mooring systems, need a large flat surface and are therefore required to be located on the side of the vessel. Also the larger mechanical mooring systems are installed next to the vessel side. The smaller mechanical mooring systems can be located on the vessels rear ends, but the force that these can provide is less due to the reduced mechanism size.

3. Case Study

For the case study the design method of Cross (2000) is used as shown in figure 1. Each step has been gone through and is discussed below.

3.1. Clarifying objectives

The main objective of this case study is to enable the Canadian ferry to sail electric. To realize this, a charging mechanism should be installed in the port such that the ferry can charge while passengers and vehicles are moving on and of the ferry. A mooring mechanism in the port is required as well to ensure that the vessel propeller can be turned off during charging. This limits the amount of charging power required and so the energy consumption costs and the required size of the charging station.

3.2. Establishing functions

Both for the charging and mooring mechanism, an analysis is done to establish the main and sub-functions that is should fulfilled in order to operate as desired. Table 1 provides an overview of the main functions and some sub-functions of the mechanisms. As can be seen, most functions are equal for both systems.

Charging mechanism	*Mooring mechanism*
Connect to the vessel	Connect to the vessel
Compensate tidal difference	Compensate tidal difference
Provide flexibility	Provide force
For misalignments	Deal with misalignments
For vessel motions	Disconnect from vessel
Transfer electric energy	
Support the charging connector	
Disconnect from vessel	

Table 1: The main functions of the charging and mooring mechanism. Also some of the sub-functions are shown.

These similar functions make it reasonable to argue that both mechanisms can be combined into one system. However, there are two conflicting functions. One sub-function of the charging mechanism is *to provide flexibility*, such that it can deal with the motions of the vessel while it is fixed to the quay. On the other hand, a function of the mooring mechanism is *to provide force*, in order to minimize the vessel motions. These conflicting functions make it hard to combine these mechanisms into one system. Even if there is great force applied, the vessel motions will not be completely eliminated, and such the charging system should always be more flexible than the mooring system to deal with these motions. Due to the limited amount of time available for this research, it is not feasible to design two separate new mechanisms. Therefore, the design of the mooring mechanism is rejected from this case study.

3.3. Setting requirements

A large list of requirements has been determined which should be satisfied by the charging mechanism in order to function as desired. A shortened version of this list is given below. These are the main requirements to show the complexity of the case study. An impression of the layout of one of the ports with the docked vessel is shown in figure 2.

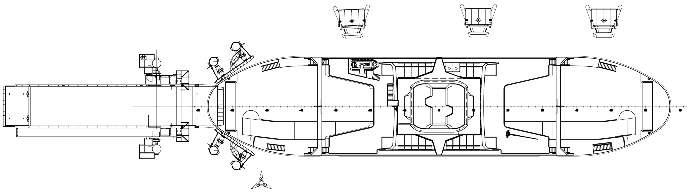

Figure 2: The layout of the port Westview and the vessel docked. All ports have and equal layout, besides the dolphins on the side of the vessel.

- The system may not cause an obstruction for passengers or vehicles moving on and of the ferry and the ramp.
- The system may not cause an obstruction for larger vessels to enter the port.
- The tidal difference in the port is 7.1m.
- The angle between the vessel centerline and the ramp centerline can vary from -7° to +7°.
- The power demand of the charger is 4 MW.
  - Option 1 LV DC: 1000V @ 4000A
  - Option 2 HV AC: 6.6 kV @ 350A
- The charging mechanism should be automated.

3.4. Determining characteristics

The characteristics of the systems can be regarded as preferences which can be satisfied is a higher of lower level. The preferences are ordered with the most important on the top. These preferences will be used later to evaluate the alternative designs that have been generated.

1. The mechanism should be as reliable as possible.
2. The mechanism should be as safe as possible.
3. The implementation of the mechanism in the port and on the vessel should be as easy as possible.
4. The design should be as generic as possible, such that it can be used for other cases.
5. The investment costs of the system itself should be as low as possible.
6. The connection time should be as low as possible.
7. Appearance of the system should be attractive and professional.

3.5. Identify the gap

When comparing the requirements for this case and the existing mechanisms from section 2.2.2, a set of functions can be identified as the gap. It is important to notice that the gap does not cover a single function, but includes this specific combination of functions which cannot be satisfied. This includes the following functions:

- Provide flexibility while charging.
- Deal with the misalignments while connecting.
- Cover the tidal difference.

The aim of the new design will be to cover this and so, that it can deal with the expected motions of this vessel, deal with the expected misalignments between the port and the vessel and cover the tidal difference of 7.1m. Furthermore it is important that the mechanism can be installed on a location where it does not cause any obstruction.

3.6. Generating alternatives

A brainstorm was executed for the three critical functions as identified in 3.5, to consider sub-solutions for each of these functions. All sub-solutions for the three critical functions and the function to transfer energy, were assembled in one morphological overview. Combining the sub-solutions lead to different concepts. The three concepts that are clearly different from each other and which seemed most feasible, where chosen to elaborate on and evaluate afterwards. An schematic idea of these concepts is shown in figure 3. Concept 1 is a crane construction where the vertical movements of the plug into the socket is automated. Concept 2 is a pantograph system connecting to the onboard spoiler. Concept 3 represents the inductive charging system, where one coil is secured to the wind wall and the second coil mounted in the vessel wall.

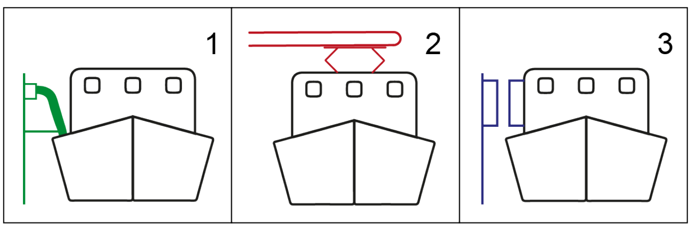

Figure 3: The concept solutions for a charging mechanism.

3.7. Evaluating alternatives

The concepts were designed into some more detail. Basic dimensions where calculated that should enable the mechanism to satisfy all requirements. A cost estimation was done for each system, based on the known costs of the already existing systems. Furthermore is was analyzed how the system could be implemented in the current port infrastructure and what modifications are required to do so. After these concept details were settled, the concepts where tested against the preferences as shown in 3.4. From this study concept 3 was rejected, mainly due to the costs that come with the mechanism. The investments costs of the system itself for concept 3, ca. 3 million euros, are approximately three times higher compared to the other two concepts and around half of the investment costs of the vessel itself. Furthermore the implementation of this concept requires more modifications to the port infrastructure compared to concept 1 and 2, and therefore also this come with high costs. Moreover, also the energy costs of concept 3 will be higher than the other concepts due to the lower efficiency of inductive charging. All together concept 3 will not be commercially attractive.

Concept 1 and 2 have both their benefits for some of the preferences, but on the total judgment they score roughly equal and no clear preferred concept is distinguished between these. Because of the limited amount time available for this research, only one concept can be chosen to further develop, which will be concept 1. This decision is based on the fact that concept 1 is derived from already existing crane systems, where concept 2 has not been developed before for vessels. Therefore it is expected that less research is required for the installation of concept 1 once all design details have been determined compared to concept 2.

3.8. Improving details

Before this concept can be developed, multiple aspects should be work out. In this part, the main focus will be to deal with the of the earlier determined critical functions from subsection 3.5. An impression of the mechanism can be found in figure 4. The clue of this concept is that the plug is secured to the wind wall by the beam indicated by number 1. This creates a crane like mechanism but with control over the plug movement. This beam can move in vertical direction, and such, also the plug. Once the vessel arrives, the plug will be lowered into the funnel shaped socket as shown in figure 4. Now the flap, indicated by number 2, will open up such that rotation of the beam is enabled. Both the rotational point and the different beam sections are equipped with springs. This ensures that the beam will always be collapsed and perpendicular to the wall in is resting stated. However, when the plug is lowered into the socket, it can rotate and extend in the funnel shaped socket such that the plug will always be directed towards the socket connection. The shape of the funnel is designed such that the plug and socket will always be connected within the misalignment interval of -7° till +7°.

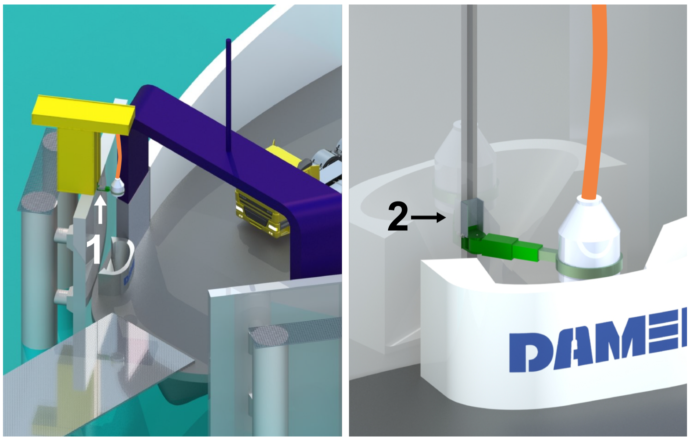

Figure 4: The final design for a charging mechanisms.

The flexibility of the mechanism should be provided by the power cable. However, as was already seen for the current existing mechanisms in section 2.2.2, the flexibility of the relatively thick power cables have proven to be critical and has caused the failure of multiple mechanisms. To gain insight in the flexibility of the power cables with respect to the expected motions of the vessel, an FEM simulation of the cables is executed. The demanded output of this simulation are the factors that might cause damages to the charging mechanism.

1. The internal stress within the power cable.
2. The resultant forces of the cables onto the plug-socket connection.

Three cable configurations have been analyzed as shown in table 2.

	LV/HV	Core CSA [mm²]	# Cores	# Cables	Weight [kg/m]	n x m
1	LV	185	1	14	1.92	2 x 7
2	LV	240	4	4	10.96	1 x 4
3	HV	150	3	1	9.04	1 x 1

Table 2: The three cable configurations analyzed in the FEM analysis

Two motions patterns of the vessel have been simulated, which have been derived from a seakeeping calculation in Qship for this vessel and the sea states that are expected in the port. Motion pattern 1, shown in equation 1, presents the worst case scenario for motions in y- and z-direction. Motion pattern 2 presents the worst case scenario for motions in x-direction, shown in equation 2.

$$\begin{aligned} d_x &= 0 \\ d_y &= 0.086 * \sin(1.24t) \\ d_z &= 0.27 * \sin(1.24t) \end{aligned} \quad (1)$$

$$\begin{aligned} d_x &= 0.015 * \sin(1.24t) \\ d_y &= 0.078 * \sin(1.24t) \\ d_z &= 0.085 * \sin(1.24t) \end{aligned} \quad (2)$$

The model used for the simulation is graphically shown in figure 5. The assumptions used for this simulation are:

- The top of the cable is fixed.
- The entire plug is moved with the prescribed displacement of motion pattern 1 and 2.
- The cable is modelled as a homogeneous material with material properties calculated from the limitations provided by the supplier such as the minimum bending radius and the maximum stress in the copper parts allowed.
- The cable is slightly buckled in its lowest point.

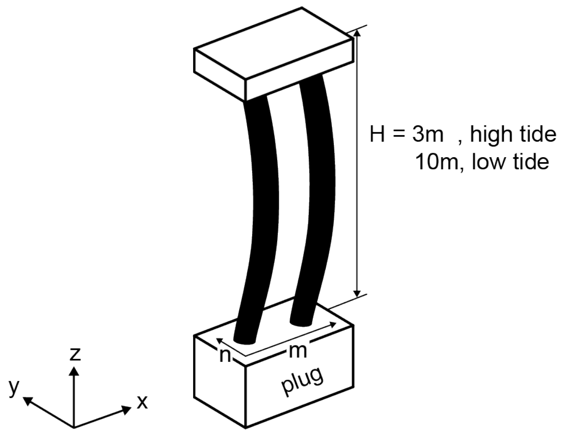

Figure 5: Set up of the model used for the FEM simulation of the cable behavior.

The outcome of the simulations show that vertical displacement of the plug is crucial. Where horizontal displacement of the plug only causes bending of the cable, vertical displacement results in buckling of the cable. Buckling results in higher internal stresses in the cable and unpredictable behavior. For longer cables the stress in the cable in reduced significantly, but the cable will perform a swinging motion which make the resultant forces largely varying and unpredictable.

The stress in configuration 2 is at it maximum only 4% below the yield strength of the sheath material. This is judged to be not a significant safety factor. Configuration 2 is therefore not considered as a possible option. Configuration 1 gives the lowest stresses and resultant forces, but the combination of fourteen parallel cables is expected to cause operational issues. For example, while a swinging motion of the cables occurs, these can get entangled easily. Cable configuration 3 is therefore chosen to be the final configuration and it is advised to investigate whether HV charging would be feasible. This demands a substantial amount of additional onboard equipment in the electric circuit such as a transformer and rectifier.

4. Guideline

The main goal of this guideline is to decrease the selection time for a charging and/or mooring mechanism for an electric vessel. To achieve this, the guideline should first of all provide an overview of all requirements that should be taken into account and the relation between them. Furthermore, the guideline should ensure that all engineers within a project team are working in the same direction towards the greater goal. This can be difficult sometimes since the engineers within a project team generally focus on different fields of interest. The guideline will be validated for a different type of vessel with respect to these goals in 4.2. First the layout of the guideline will be set up in 4.1.

4.1. Guideline layout

Using the knowledge gained during the case study, the guideline for the selection of a charging and mooring mechanism is constructed. Four main observations with respect to the design method can be distinguished form the case study.

1. The orientation phase is not necessary. At the time that the guideline will be used by the engineers, they already have designed the electric vessel itself. So they will be well oriented when starting this selection process.
2. The phase to determine limitations is complex and demanding. The requirements are strongly related with each other and without any guidance in this process it is easy to overlook some influential factors or to lose track of the relations between these requirements.
3. The method assumes that a new system will be designed in any case. The guideline should provide more interaction with the current existing mechanisms, such that the engineers can easily see if there is a suitable system already available. Only if this is not the case, a new system should be developed.
4. The design phase will not be used in practice. This guideline is set up to serve the Damen engineers. Damen is a shipyards and not a charging or mooring mechanism company. It is unlikely that Damen will actually design these systems in house. When a suitable system cannot be found

from the mechanisms that are currently available, the Damen engineers should clearly identify the gap. This can be used to easily show a mechanism supplier what kind of system is searched for by the engineers.

Using these lessons learned, the layout of the guideline has been set up as shown in figure 6.

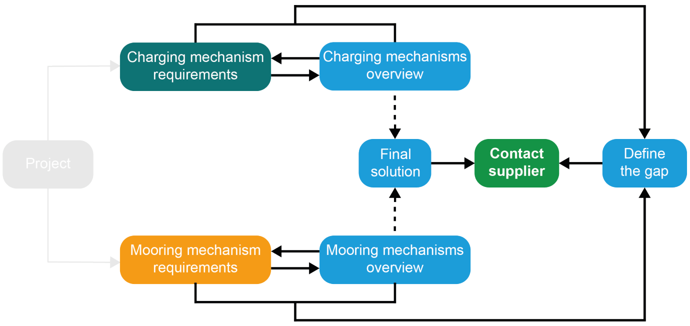

Figure 6: The layout of the guideline.

The figure starts with the project, which is the reason to look into the guideline in the first place. One can start either at the charging mechanism requirements or the mooring mechanism requirements, depending on what is demanded by the project. While setting these requirements, there will be an continuous interaction with the overview of currently existing mechanisms to check if a suitable mechanism is commercially available already. If a suitable mechanism is found, the supplier of this system should be contacted. If no mechanism was found, one should identify the gap between the existing mechanism and the demanded mechanism. This gap should be used to negotiate with a supplier for the development of a new mechanism.

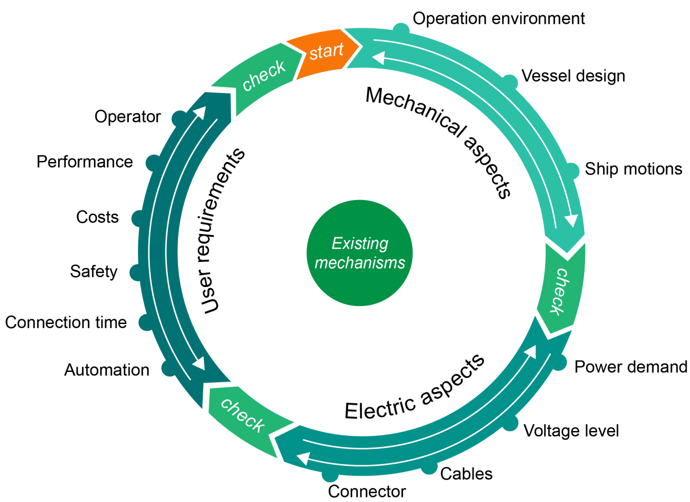

Figure 7: The iteration circle to set the charging requirements.

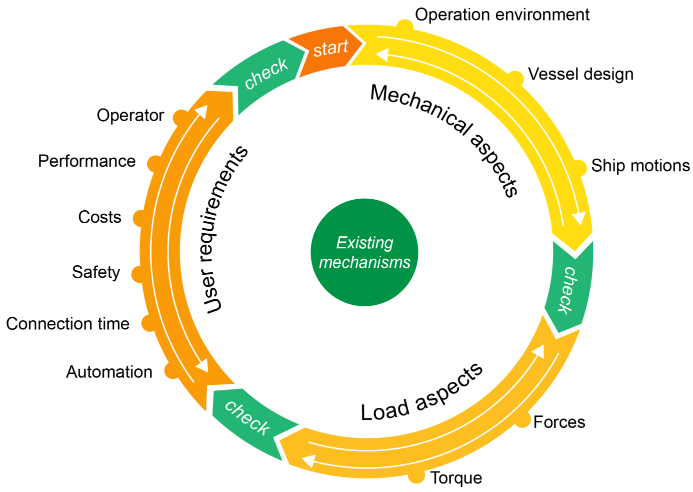

Figure 8: The iteration circle to set the mooring requirements.

As stated before, setting the requirements is a complex and demanding process where guidance is desired. To do so, the chapters on requirements for the charging and mooring mechanism are arranged according to the iteration circles from figure 7 and 8. The clue of these iteration circles is that the requirements that are relatively easy to determine, are set first. Doing so, the risk of wasting time and money on unfeasible or unprofitable projects is limited. The mechanical aspects for instance, are mainly determined by looking at graphics of the port layout and the vessel design to see where a mechanism could be installed. The electrical requirements need in general some more calculations, and such this step will take more time in general. The user requirements come last due to the amount of time generally required for this phase. Extensive negotiations with the customer are required to determine these, who can be located all over the world. Furthermore this order enables to start a project before there is a customer contracted to for the vessel. The arrows within a category the various subjects are related and feedback might be required. After each category, the overview of available mechanisms should be consulted to check whether a suitable mechanism already exists, if the requirements are possibly too tight of whether a new system is required.

4.2. Guideline validation

The guideline was validated while searching for a charging mechanism for an electric tug which is currently in development. The guideline is validated by the main and sub goals as defined in the beginning of this section.

- *Provide insight in the necessary requirements and their relationship.*
  The requirements became more clear than it was before. For example, the initial location of the plug that was imagined, was changed due to the insight of all aspects that influence this location.

- *The entire project team working in the same direction.*
  During the test there was a clear collaboration between the engineers from different fields of interest. The charger power output for instance, was evaluated from electrical, mechanical and business point of view.

- *Decrease the selection time of the charging mechanism.*
  The test session resulted in one preferred mechanism, although the existing version does not deliver the demanded power level. Currently Damen is negotiating with the supplier of the mechanism for a new design of this system, with a higher power output.

The main goal of the guideline was reached since the two hour session already resulted in a demanded charger design. For other projects, at least multiple meetings with various suppliers preceded before coming to this point. The sub goals where achieved as well. All requirements that should be taken into account and the relation between them became more clear than it was before. The project team was also collaborating in one direction, although there were no major disagreements before the test of the guideline.

5. Conclusion

The goal of the research was to develop a guideline to ease to selection of a charging and mooring mechanism for electric vessels. This guideline was developed based on the knowledge gained during a case study for a ferry and validated for an electric tug. The guideline proved to be beneficial during the validation test since the session ended with a preferred mechanism which is currently discussed with the supplier. The sub goal of this research was to design a charging mechanism for the BC Ferries. A conceptual design was delivered, but this should be worked into more detail before it can actually be developed. Furthermore, this research provided new research into the flexibility of relatively large power cables. Power cables that are currently classified as flexible are rather supposed to be bend in a certain position and leave it that way. Continuous deformation of the cable is a rather new subject with different consequences for the cable behavior.

The guideline provides an overview of all influential factors in finding a suitable mechanism for the cases that were analyzed during this research. However, since this field of technology is rather new it is likely that in future cases additional factors will play a role that have not been mentioned yet. These should be adopted in the guideline. Equal applies to new developed mechanisms, which will definitely come on the market in the coming years. These should be incorporated in the overview of existing systems. Furthermore, more research should be done to the behavior of continuously moving power cables. This includes for example the material properties of all layers in the cable and practical experiments of the FEM analysis that was done. Practical experiments will be important since the cable motions are mainly non-linear. This behavior is hard to predict by a computer model, since this is behavior is initiated by imperfections.

Acknowledgements

This research was created with the help of experts and the facilities offered by the TU Delft and Damen Shipyards Gorinchem.

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F
Generic design guideline

Guideline for the development of an electric vessel.

On how to select a charging and mooring mechanism for an electric vessel.

This guideline has been written to ease the development and implementation of electric vessels. In general, for the operation of electric vessels a charging and a mooring mechanism should be installed in the ports where the vessel will be docked. Various mechanisms are commercially available for both functions. However, which mechanism is optimal is strongly dependent on the port and vessel for which it will be used.

The goal of this guideline is to ease the selection of a charging and mooring mechanism for a specific case. This should help to meet the increasing demand for electric vessels in the near future. To do so, this guideline provides a support on how to specificy the requirements for these systems and show which aspects should be taken into account. Furthermore an overview of the mechanisms that are currently available is provided in the appendix.

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Layout:

1

Charging mechanism requirements

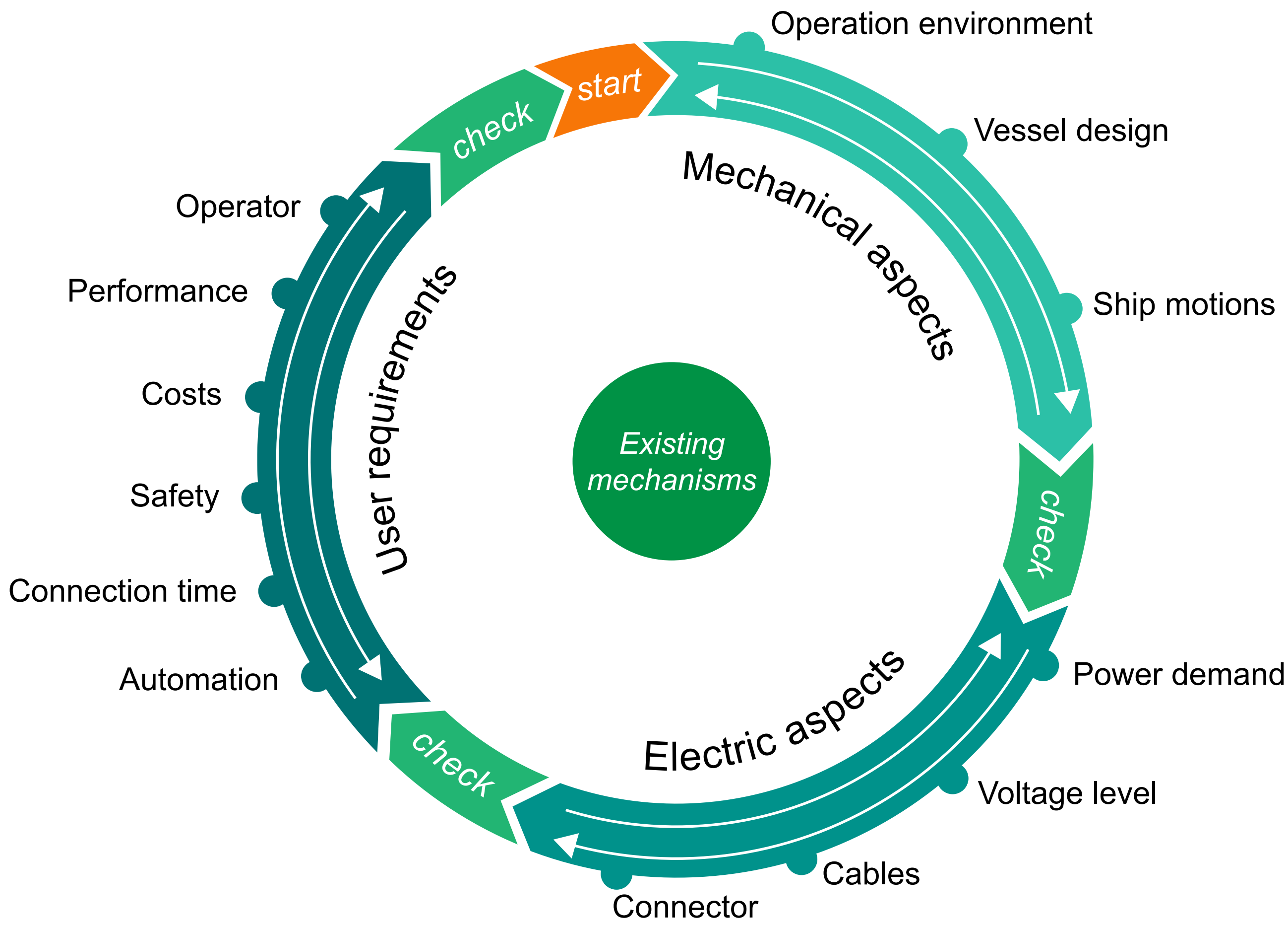
The design cycle

The requirements for the charging mechanism should be determined by the using the design cycle on the right. Since requirements are often related to each other, it has turned out that it can be hard to order these. By following this cycle, the work flow will be structured and an clear insight in the requirements and their relations is established. The fundamentals of the cycle are describe below. Following in this chapter, a more detailed description of each part is provided.

The first step of the circle is the mechanical aspects, which cover the limitations of the charger with respect to its weight, dimensions and required flexibility. Most of these aspects can be simply found by looking at port and vessel drawings and some basic weather information. While determining the requirements on the mechanical aspects, it can occur that new insights force you to revise the requirements form previous sections. Once all requirements for the mechanical aspects have been determined, it is important to check in appendix A whether there are charging mechanisms are available satisfying these. If already no mechanism is available, try to identify the gap and consider if the requirements are not too demanding.

Afterwards one should determine the requirements on the electrical aspects. Here some more calculations come into play and one should gain some knowledge into the grid properties on the ship and shore side. Just as it was for the mechanical aspects, it might be needed to revise the additional requirements as well. However, to keep the process going, try to stay within the electric aspects. The mechanical aspects have already been taught trough well in this stage and should be left alone for now. Once the requirements for electric aspects have been determined, appendix A should again be consulted to check which mechanisms that where suitable before, are still sufficient now that also the electrical requirements are know. If no mechanism is available, try to identify the gap and consider if the requirements are not too demanding.

Last to determine are the user requirements. These can be estimated on is own, but proper consultation with the customer is required to establish the exact numbers. Once these have been determine, a last check at appendix A is required to see for suitable charging mechanisms. The chance of not find a suitable mechanism is substantial after passing the design cycle just once. Form this point, one should iterate the design cycle. Check if there are mechanisms suitable if some of the requirement are modified. For example if the location of the plug is changed, the charging time is extended or the investment costs are raised.


start
check
Mechanical aspects
Operation environment
Vessel design
Ship motions
check
Electric aspects
Power demand
Voltage level
Cables
Connector
check
User requirements
Operator
Performance
Costs
Safety
Connection time
Automation
Existing mechanisms

Operation Environment

What are the environmental conditions that the vessel and the charger will be exposed to? Thinkof conditions such as:

- Wind (Bft, direction)
- Waves (height, frequency, direction)
- Precipitation
- Temperature range
- Humidity
- Tide variations
- Snow on the ground
- Frost

What is the layout of the port(s) where the vessel will be docked?

- Quay dimensions
- Quay height (with tide variation)
- Quay construction
- Vessel orientation in the port. Is this consistent of varying?
- Constructions in the port
- Which area can be used?

Use this information to identify possible locations on the shore for the installation of both the charging mechanism, but also for the charging station where equipment such as transformers and converters are installed. Take into account that the charger and charging station are of significant size and weight, so sufficient space and proper foundation is necessary.

Fill the following table to get an overview of the possible locations.

Location	Pro’s	Con’s

Vessel Design

Next to the charging mechanism on the shore, there is of course a connecting mechanism required on the vessel. To determine where this system should be installed, multiple factors should be taken into account. These are listed below.

- Where is space available?
- Where does it obstruct passengers/staff/vehicles?
- Which location is close to the shore when docked?
- Where is the switchboard installed?
- Should humans around the charger be protect from induction?
- Where is the system easy to reach for manual connection?

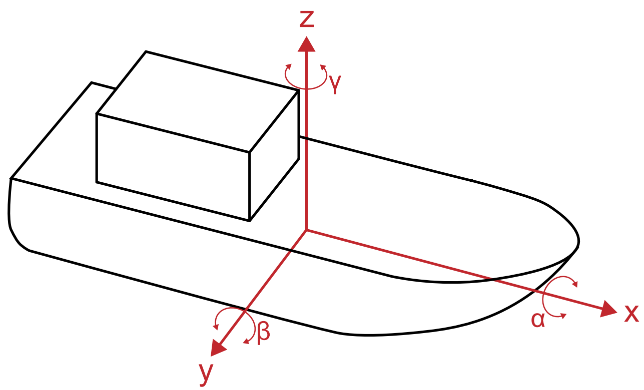
Generally there are multiple locations possible with difference advantages and disadvantages. List multiple feasible locations and identify their positive and negative aspects. Try to think out of the box in this stage. Are there aspects to the standard design that could be modified?

This part should only be used when the design circle has already been gone through once.
For some power supply cases an onboard rectifier and/or transformer might be required. If this is the case, think also about locations on the vessel where these could be installed.

Fill the following table to get an overview of the possible locations.

Location	Pro's	Con's

Ship Motions



The ship motions of the vessel are defining the required flexibility of the charging system. These can be determined in two ways described below.

1. Real life measurement.

If the electric vessel is supposed to replace a comparable vessel, the motions of the vessel when it is docked can possibly be measured on board of the old vessel. To get reliable testing results, it is important that measurements are done during all possible sea states and weather conditions at which the vessel will operate. In the case that there is no vessel to replace, or the operating environment is not yet know, simulation is required.

2. Sea keeping simulation.

A sea keeping simulation can predict the motions of the vessel in all six degrees of freedom. Important input for this simulation is:

- Hull shape
- Loading conditions
- Wave spectrum (height, frequency and direction)

The initial demanded output of the simulation, is the RAO of the motion of the socket location (x, y, z) on the vessel.

- RAO: x_abs_motion_vessel {x, y, z}
- RAO: y_abs_motion_vessel {x, y, z}
- RAO: z_abs_motion_vessel {x, y, z}

The RAO's should be processed using the wave spectrum to determine the expected motions of the socket connection. This should be used to check if the mechanisms are providing suitable flexibility.

Notice that the exact motion is depending on the charging mechanism location on the vessel. Once the exact location of the system is chosen, the required flexibility should be verified.

Check

Check in appendix A if there are mechanisms available satisfying the requirements that have been set until now. Make a quick list of mechanisms that do seem suitable from this point. This list can be easily used when the additional requirements have been set, to check if these mechanisms are still appropriate.

If there are no mechanisms available, try to identify the gap between the existing mechanisms and the requirements. Argue whether the requirements that have been are set realistic. Small modifications to existing mechanisms are often possible in consultation with the supplier. However, if the required aspects are largely differentiating, you should wonder if the requirements are perhaps too demanding.

Even if there are no mechanisms available for the requirements, continue with the following parts of the design cycle. This will provide you the remaining requirements that are needed in the case a new charging mechanism should be developed.

Suitable mechanisms

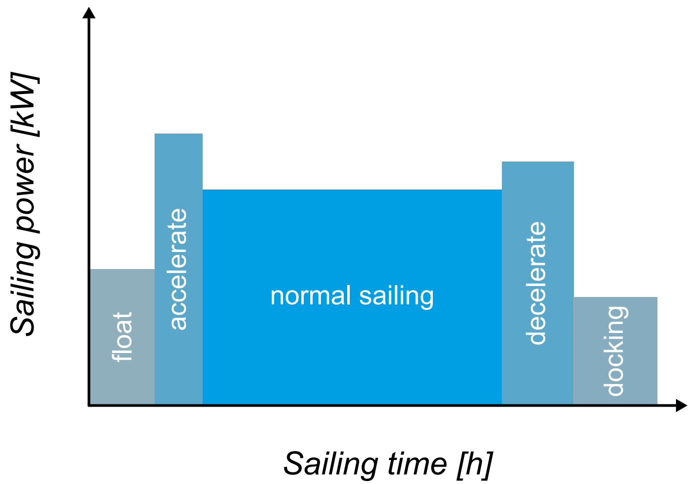
Power Demand

To determine the power demand of the vessel, one should set up a operational profile for the vessel. The operation profile can look like the block diagram below. The energy usage of the vessel in kWh, is a product of the sailing power and the sailing time.

For some vessel types f.i. shuttle ferries, one operation profile will be sufficient. But for vessel types with a varying operation, multiple operational profiles might be needed to get a clear insight in the energy usage.

Influential parameters for the operation profile are:

- Vessel loading
- Vessel speed
- Wind direction and speed
- Waves direction and height



Next to the energy usage of the vessel one should think about the time available for charging and what the charging strategy will be. For example a ferry can charge short after each stop, or make multiple trips and charge longer afterwards.

The energy usage that should be supplemented and the time available for charging will together provide you the power demand of the charging mechanism. Fill out the table on the right to get a clear overview of the possible charging powers and their principles.

	Power comsumption vessel [kW]	Lowest battery level [%]	Sailing time without charging [h]	Max. charging time [h]	Demanded charger power [kW]
Option A					
Option B					
Option C					
Opt....					

Voltage Level

When the required charger power has been determined, it is important to consider whether the power is supplied in LV (Max. 1000 VDC) or in HV and if the electricity supply is DC or AC. The decision has major implications on aspects such the charger flexibility, the required safety measures and the required equipment on shore and the vessel. The table below gives a quick impression of the consequences of certain decisions.

	LV DC	LV AC	HV AC		HV DC	Induction (AC)
	Consider when on-board system is AC or DC.	Consider when on-board system is AC.	Consider when on-board system is AC of DC.		Not in practice	Consider when inductive charging is preferred.
Power transfer with respect to charger dimensions	Medium	Medium	High			Low
Cable requirements	Demanding	Demanding	Low			Low
Safety measures	Low	Low	Demanding			Low
	No galvanic isolation	No galvanic isolation	Galvanic isolation			Galvanic isolation
On-board equipment						
Transformer (ca. 2t/MW)	No	No	Yes	Yes HF		No
Rectifier	No	Yes	Yes	Yes		Yes
HF Inverter	If on-board system is AC.	No	No	Yes		No
Extra rectifier	No	No	No	Yes		No
On shore equipment, without shore battery						
Transformer	Yes	Yes	Yes			Yes
Rectifier	Yes	No	No			Yes
Inverter	No	No	No			Yes
On shore equipment, with shore battery						
Grid transformer	Yes	Yes	Yes			Yes
Grid rectifier	Yes	No	No			Yes
Battery transformer	No	No	Yes			No
Battery inverter	No	Yes	Yes			Yes

Aspects that should be considered for determining the electricity supply are:

- What is the maximum power that can be provided by local grid?
- Is the size and weight of additional on-board equipment limited?
- Should a on shore battery be installed? -> What are the peak power costs,

Fill out the following table to get an overview of the possibilities

	Voltage [V]	Current [A]	AC/DC	Onboard equipment	On-shore equipment
Option A					
Option B					
Opt....					

Cables

The power cables that should be used are especially important to consider for new build systems and for system where the cable should be flexible. In the case that a proven mechanism is bought from a supplier, this comes probably with a cable that suits the system.

The dimensions of the cable are mainly determined by the conductor size and the amount of conductors, which depends on the desired current transfer. For the required conductor size, check the BV standard NR 467 Rules for the Classification of Steel Ships, Part C, Chp 2, Sec 3. Other cable requirements, such as the required material properties, can be found in IEC 80005-1.

Influential parameters for cable selection:

- Current transfer
- Voltage level
- AC or DC
- Operation temperature
- Data transfer between ship and shore
- Amount of cables
- Required flexibility
- Required bending radius
- Charging time

To get an overview of the cables that could possible be used, fill out the table on the right page.

Fill out the following table to get an overview of the possibilities

	Conductor CSA [mm^2]	# Conductors	Rated current [A]	Corrected current	OD cable [mm]	# Cables	Total weigth [kg/m]	Bending radius [mm]	Fibers?
Option A									
Option B									
Opt....									

Connector

Just like the cables, also this section is mainly important for new build systems. In the case that a proven mechanism is bought from a supplier, this comes probably with a connector that suits the system.

For new build system it is important to take into account the requirements form the standards IEC80005-1 and IEC62613-1. These contain requirements that should ensure safe operation in normal operation conditions and in the case of a default. Also the tests that should be executed to test a new designed charger are described in these standards.

Influential parameters for the connector selection:

- Current transfer
- Voltage level
- AC or DC
- Operation temperature
- Data transfer between ship and shore
- Max. amount of plugs
- Required amount of pilot pins

To get a clear overview of the connector demands, fill out the table on the right.

Fill out the following table the get a clear summary of the connector requirements.

Voltage level [V]	
Current level [A]	
Manual operation allowed?	
Max. manual force allowed [N]	
Max. # plugs	
Compatible to multiple vessels	
Data transfer?	
Min. # of pilot pins.	

Check

Check in appendix A if there are mechanisms available satisfying the requirements that have been set until now. Make a quick list of mechanisms that do seem suitable from this point. This list can be easily used when the additional requirements have been set, to check if these mechanisms are still appropriate.

If there are no mechanisms available, try to identify the gap between the existing mechanisms and the requirements. Argue whether the requirements that have been are set realistic. Small modifications to existing mechanisms are often possible in consultation with the supplier. However, if the required aspects are largely differentiating, you should wonder if the requirements are perhaps too demanding.

Even if there are no mechanisms available for the requirements, continue with the following parts of the design cycle. This will provide you the remaining requirements that are needed in the case a new charging mechanism should be developed.

Suitable mechanisms

User requirements

The user requirements are not so much on whether the charger will work, but rather on the acceptance of the client. Since different customers have different priorities, this section is in general best to determine in consultation with the customer. However, also when there have not been contracted a customer yet, it will pay of to have a look at it already to get insight in the aspects that should be taken into account.

Automation

Generally three levels of automation can be distinguished: Manual, automated and autonomous operation. The level of automation is an important aspect to determine since this will have a great impact on the remaining user requirements.

Manual

At least one person is needed to physically assist the charger to make the connection. It can be that the charger provides support to decrease the required physical effort, but the connection cannot be made without the physical interaction.

Automated

At least one person is required to control the charger, but this does not include any physical interaction. This could for instance be a controller who pushes a button to activate the charging mechanism after which the connection is made automatically.

Autonomous

There is no human interaction required to control the charging mechanism. The charging mechanism is able to detect when the vessel is in the correct position to make the connection and when the vessel is willing to leave again, without any signals given by humans.

Connection time

What is the maximum time allowed for connecting the charger to the vessel? And what is the maximum disconnection time?

Safety

Safety is of course a broad but very important aspect. Multiple standards can be consulted to check the safety standards, especially for the electrical safety. These are for example IEC80005-1 and IEC62613-1. To provide as much safety as possible, there are six main categories that on should take into account.

- Mechanical safety, during normal operation
- Mechanical safety, in case of failure.
- Electrical safety, during normal operation.
- Electrical safety, in case of failure.
- Sufficient testing before installation.
- Sufficient testing during the operational lifetime.

Furthermore it is important to determine the categories to which safety should be offered. This will probably include at least all humans on and near the vessel. But possibly also other groups such as vehicles, the flora and fauna in the port or special cargo.

Costs

To make electric vessels attractive for customers, financial aspects play a major role. Questions as the ones below should be taken into account. Three main costs aspects can be distinguished :

- The investment costs of the system itself.
- The installation costs of the system in the port.
- The operational costs of the system.

The first to aspects define the CAPEX of the system. One should notice that the investment costs for the a specific system will be comparable for all cases. However the installation costs can be widely varying for this systems due to the port infrastructure. The last aspect covers the OPEX of the system.

Performance and Durability

The performance of the charger can be basically described as the rate: *failed connections / total connection attempts.* Failed connections include events in which the plug cannot be connected to the charger, but also events in which the physical connection is made but no energy is transferred. Aspects that influence the performance of the charger are:

- Mechanical construction of the charger
- Charger power system

- Material properties
- Control system hardware
- Control system software
- Charger flexibility
  - *Deal with moving vessel*
  - *Deal with varying vessel alignment*

The first five aspects cover the entire construction of the charger, which should be designed such that it can operate properly in the conditions that is it designed and will not get damaged. The charger flexibility is of major importance to make a connection and to keep the connection stable during charging.

Additional requirements from the operator

The operator often has specific thoughts on how he will use its vessel. It is important that these are discovered before development of the vessel since this may affect the design of the vessel, while the operator is not aware of this.

Check

Check in appendix A if there are mechanisms available satisfying the requirements that have been set. Make a quick list of mechanisms that do seem suitable from this point.

If there are no mechanisms available, try to identify the gap between the existing mechanisms and the requirements. Argue whether the requirements that have been are set realistic. Small modifications to existing mechanisms are often possible in consultation with the supplier. However, if the required aspects are largely differentiating, you should wonder if the requirements are perhaps too demanding.

Iteration of the Design Cycle

Now that the design cycle is gone through entirely, the complete set of requirements has been established. However, it is likely that initially no suitable mechanism is found. Go through the circle once more and try to modify some requirements. Probably already multiple options have been found for some requirements during the first cycle. Revise the requirements to check if there can be found a suitable mechanism for this case. For instance move the location of the socket on the vessel or change the power level. Continue this iteration until one or more suitable mechanism have been found or when it can be stated that no suitable mechanism does exist.

When one or multiple mechanisms have been found, consult the producing companies of these mechanisms.

If there is no mechanism commercially available which is suitable for this project, continue to chapter 3. This chapter described how the define the gap that can be used to contact suppliers for a new mechanism.

Suitable mechanism

2

Mooring mechanism requirements

The design cycle

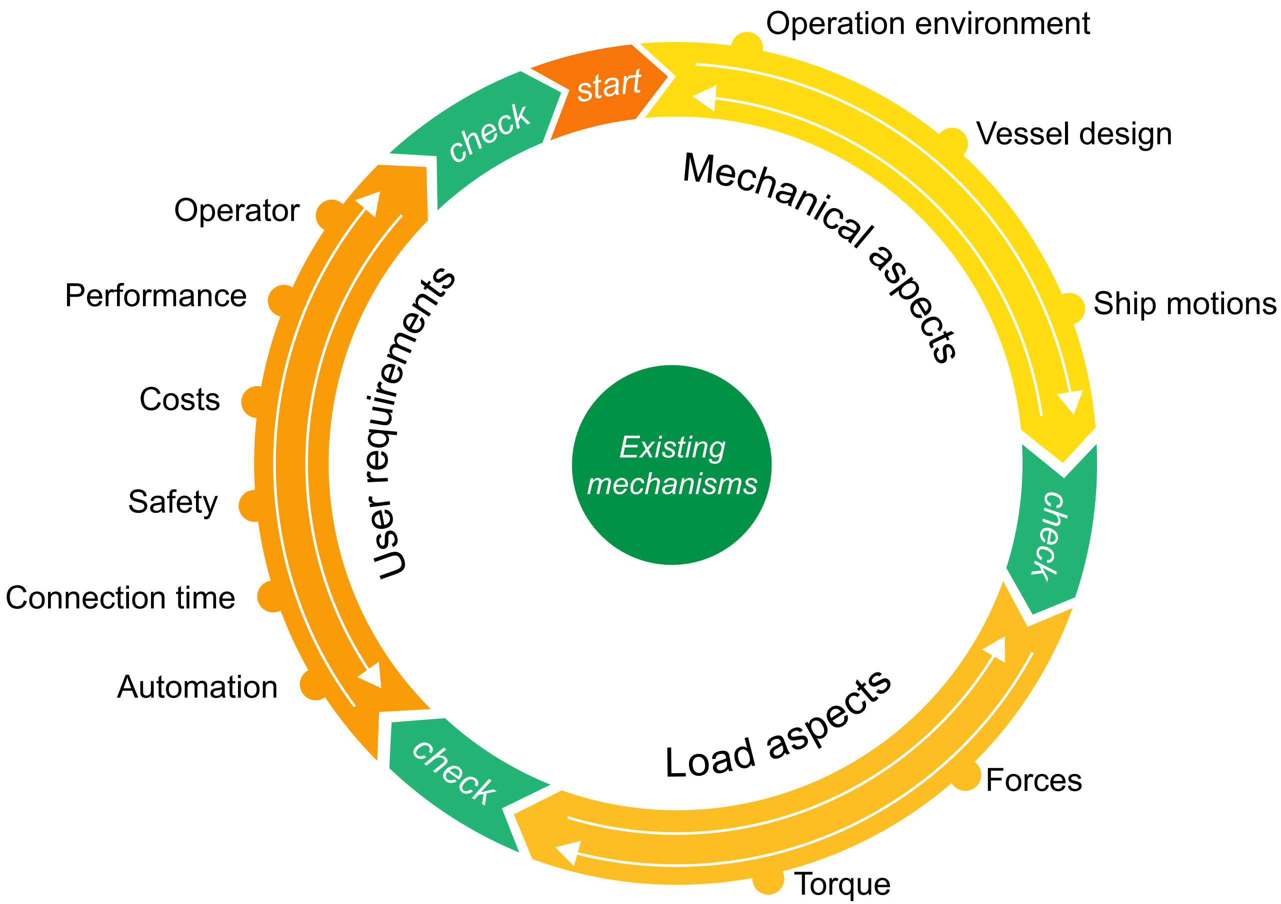
The requirements for the mooring mechanism should be determined by the using the design cycle on the right. This will seem quite similar to the design cycle of the charging mechanism, but the outcome for some aspects can be very different. For instance, the location of the charging system is mainly determined by the ability to connect the grids, while the location of the mooring mechanism should be able to withstand the mooring forces. For this reason it is important that also this circle is gone though.

The first step of the circle is again to determine the mechanical aspects. First the operation environment is analysed to check where space is available in he port to install a mooring mechanism and to which environmental conditions this system will be exposed. Secondly on should look investigate the vessel design to see where the onboard mooring connection can possibly be made. This does not need to be a bolder but can for instance also be a flat surface on the outside of the vessel where a vacuum mooring system can be connected. Depending on the mooring orientation, one could now already check of the port and vessel location are corresponding in some way. The last part are the vessel motions. These should be calculated mainly to check the varying alignment between the vessel and the mooring system. When all mechanical requirements have been set,appendix B should be consulted to check which exiting mooring mechanism would be suitable for this specific case.

The second part covers the loads aspects, where the required holding force of the mooring system is determined. Both the forces in x-, y- and z-direction and the torque around these axes should be determined from a sea keeping calculation. Once the loadings have been determined, take another look at appendix B. Determine which of the systems that where chosen before are still suitable now that the required holding force is known.

The last step covers the user requirements. Comparable to the charging mechanism, these do not focus on the physical feasibility but rather on the customer desires. This includes among others the desired level of automation, the safety regulations and the financial restriction. To set up well defined requirements, this should often be done in collaboration with the client. However, if there is no contracted customer yet, try to make a global estimated of these requirements. Afterwards, appendix B should be checked once more to see which currently available mechanisms are still feasible for this case.

It is likely that no suitable solution has been found after going though the circle just once. Now the iteration starts. Go through all the requirements once more and try to change some of them. Can a feasible solution be found now? Go on iterating until one or more suitable products have been found, or until it is sure that no suitable solution is available yet.


start
check
Mechanical aspects
Operation environment
Vessel design
Ship motions
check
Load aspects
Forces
Torque
check
User requirements
Operator
Performance
Costs
Safety
Connection time
Automation
Existing mechanisms

Operation Environment

What are the environmental conditions that the vessel and the mooring mechanism will be exposed to? Think of conditions such as:

- Wind (Bft, direction)
- Waves (height, frequency, direction)
- Precipitation
- Temperature range
- Humidity
- Tide variations
- Snow on the ground
- Frost

What is the layout of the port(s) where the vessel will be docked?

- Quay dimensions
- Quay height (with tide variation)
- Quay construction
- Vessel orientation in the port. Is this consistent of varying?
- Constructions in the port
- Which area can be used?

Use this information to identify possible locations on the shore for the installation of the mooring mechanism. One should take into account that the force on the mooring mechanism can be significant and that the foundation on which the mechanism is placed, should support this. The exact forces are calculated later in the part on the load aspects.

Fill the following table to get an overview of the possible locations.

Location	Pro’s	Con’s

Vessel design

What is the design of the vessel and what are possible locations to install a mooring mechanism or at least a connection point to the mooring mechanism in the case this is placed on shore? To determined the location, take into account the following topics.

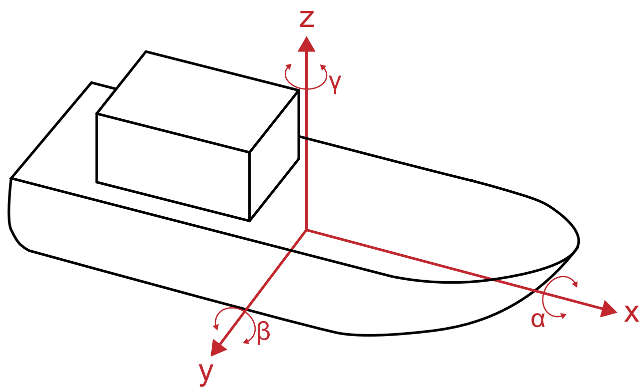
- Where is free space available on the vessel?
- The mooring mechanism should not obstruct the path for people or vehicles on the vessel.
- The installation should be used in all docking orientations.
- In case of manual operation, the installation should be each to reach.
- Which parts of the vessel structure are expected to be strong enough to handle the mooring forces?

Try to think out of the box in this stage. Are there aspects to the standard design that could be modified?

Fill the following table to get an overview of the possible locations.

Location	Pro's	Con's

Ship motions



The ship motions of the vessel define the required flexibility of the mooring system. These can be determined in two ways described below.

1. Real life measurement.

If the electric vessel is supposed to replace a comparable vessel, the motions of the vessel can possibly be measured on board of the old vessel. To get reliable testing results, it is important that measurements are done during all possible sea states and weather conditions at which the vessel operates. In the case that there is no vessel to replace, or the operating environment is not yet know, simulation is required.

2. Sea keeping simulation.

A sea keeping simulation can predict the motions of the vessel in all six degrees of freedom. Important input for this simulation is:

- Hull shape
- Loading conditions
- Wave spectrum (height, frequency and direction)

The initial demanded output of the simulation, is the RAO of the motion of the socket location (x, y, z) on the vessel.

- RAO: x_abs_motion_vessel {x, y, z}
- RAO: y_abs_motion_vessel {x, y, z}
- RAO: z_abs_motion_vessel {x, y, z}

The RAO's should be processed using the wave spectrum to determine the expected motions of the mooring connection. This should be used to define the misalignments between the vessel and the shore while mooring. Notice that the tidal difference should also be included in this variation.

Notice that the exact motion is depending on the connection location on the vessel. Once the exact location of the system is chosen, the required flexibility should be verified.

Check

Check in appendix B if there are mechanisms available satisfying the requirements that have been set until now. Make a quick list of mechanisms that do seem suitable from this point. This list can be easily used when the additional requirements have been set, to check if these mechanisms are still appropriate.

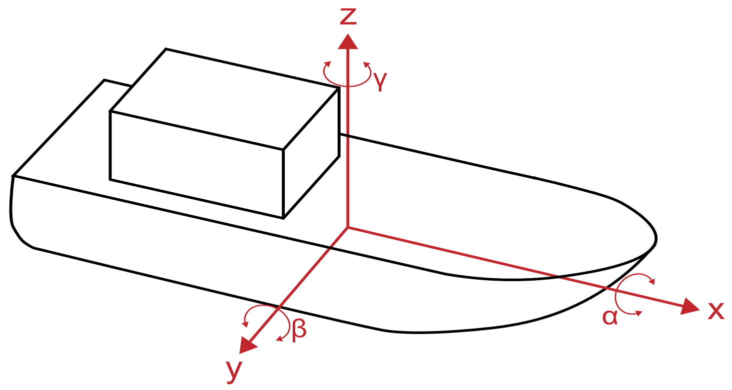
If there is no mechanism available, try to identify the gap between the existing mechanisms and the requirements. Argue whether the requirements that have been are set realistic. Small modifications to existing mechanisms are often possible in consultation with the supplier. However, if the required aspects are largely differentiating, you should wonder if the requirements are perhaps too demanding.

Even if there are no mechanisms available for the requirements, continue with the following parts of the design cycle. This will provide you the remaining requirements that are needed in the case a new charging mechanism should be developed.

Suitable mechanisms

Forces and Torque

The forces on the mooring mechanism should be calculated by a sea keeping simulation.



A sea keeping simulation can predict the motions of the vessel in all six degrees of freedom. Important input for this simulation is:

- Hull shape
- Loading conditions
- Wave spectrum (height, frequency and direction)

The initial demanded output of the simulation, is the RAO of the force and torque of the centre of gravity on the vessel.

- RAO: F_surge_abs@COG
- RAO: F_sway_abs@COG
- RAO: F_heave_abs@COG
- RAO: F_roll_abs@COG
- RAO: F_pitch_abs@COG
- RAO: F_yaw_abs@COG

The RAO's should be processed using the wave spectrum to determine the expected force on the mooring system.

Notice that the exact force is depending on the connection location on the vessel and the amount of connection points. Once the exact location of the system is chosen, the required flexibility should be verified.

Check

Check in appendix B if there are mechanisms available satisfying the requirements that have been set until now. Make a quick list of mechanisms that do seem suitable from this point. This list can be easily used when the additional requirements have been set, to check if these mechanisms are still appropriate.

If there is no mechanism available, try to identify the gap between the existing mechanisms and the requirements. Argue whether the requirements that have been are set realistic. Small modifications to existing mechanisms are often possible in consultation with the supplier. However, if the required aspects are largely differentiating, you should wonder if the requirements are perhaps too demanding.

Even if there is no mechanism available for the requirements, continue with the following parts of the design cycle. This will provide you the remaining requirements that are needed in the case a new charging mechanism should be developed.

Suitable mechanisms

User requirements

The user requirements are not so much on whether the mechanism will work, but rather on the acceptance of the client. Since different customers have different priorities, this section is in general best to determine in consultation with the customer. However, also when there is not contracted a customer yet, it will pay of to have a look at it already to get insight in the aspects that should be taken into account.

Automation

Generally three levels of automation can be distinguished: Manual, automated and autonomous operation. The level of automation is an important aspect to determine since this will have a great impact on the remaining user requirements.

Manual
At least one person is needed to physically assist the mooring system to make the connection. It can be that the mooring system provides support to decrease the required physical effort, but the connection cannot be made without the physical interaction.

Automated
At least one person is required to control the mooring system, but this does not include any physical interaction. This could for instance be a controller who pushes a button to activate the mooring mechanism after which the connection is made automatically.

Autonomous
There is no human interaction required to control the mechanism. The mooring mechanism is able to detect when the vessel is in the correct position to make the connection and when the vessel is willing to leave again, without any signals given by humans.

Connection time

What is the maximum time allowed for the mooring to the vessel? And what is the maximum disconnection time? Take into account that the charging mechanism can generally only be connected after the vessel is moored. Therefore the connection time of the mooring mechanism is effecting the time left for charging.

Safety

To provide as much safety as possible, there are five main categories that should be taken into account.

- Mechanical safety, during normal operation.
- Mechanical safety, in case of failure.
- Electrical safety, in case of failure.
- Sufficient testing before installation.
- Sufficient testing during the operational lifetime.

Furthermore it is important to determine the categories to which safety should be offered. This will probably include at least all humans on and near the vessel. But possibly also other groups such as vehicles, the flora and fauna in the port or special cargo.

Costs

To make electric vessels attractive for customers, financial aspects play a major role. Questions as the ones below should be taken into account. Three main costs aspects can be distinguished:

- The investment costs of the system itself.
- The installation costs of the system in the port.
- The operational costs of the system.

The first to aspects define the CAPEX of the system. One should notice that the investment costs for the a specific system will be comparable for all cases. However the installation costs can be widely varying for this systems due to the port infrastructure. The last aspect covers the OPEX of the system.

Performance and Durability

The performance of the charger can be basically described as the rate: *failed connections / total connection attempts.* Aspects that influence the performance of the mooring mechanism are:

- Mechanical construction of the system
- Material properties
- Control system hardware
- Control system software

User requirements

- Mooring system flexibility
  - Deal with varying vessel alignment

The first five aspects cover the entire construction of the mechanism, which should be designed such that it can operate properly in the conditions that is it designed and will not get damaged.

Additional requirements from the operator

The operator often has specific taughts on how he will use its vessel. It is important that these are discovered before development of the vessel since this may affect the design of the vessel, while the operator is not aware of this.

Check

Check in appendix B if there are mechanisms available satisfying the requirements that have been set until now. Make a quick list of mechanisms that do seem suitable from this point. This list can be easily used when the additional requirements have been set, to check if these mechanisms are still appropriate.

If there is no mechanism available, try to identify the gap between the existing mechanisms and the requirements. Argue whether the requirements that have been are set realistic. Small modifications to existing mechanisms are often possible in consultation with the supplier. However, if the required aspects are largely differentiating, you should wonder if the requirements are perhaps too demanding.

Iteration of the Design Cycle

Now that the design cycle is gone through entirely, the complete set of requirements has been established. However, it is likely that initially no suitable mechanism is found. Go through the circle once more and try to modify some requirements. Probably already multiple options have been found for some requirements during the first cycle. Revise the requirements to check if there can be found a suitable mechanism for this case. Continue this iteration until one or more suitable mechanism have been found or when it can be stated that no suitable mechanism is available.

When one or multiple mechanisms have been found, consult the producing companies of these mechanisms.

If there is no mechanism commercially available which is suitable for this project, continue to chapter 3. In this chapter it is described how to set up the gap that could used to contact the suppliers of these mechanisms.

Combination of a charging and mooring mechanism

The charging and mooring mechanism for the electric vessel should be used at the same time, next to each other. Check if this would be feasible for the mechanisms that have been found. If this is not the case, revise both the charging and mooring mechanisms once more, to check if other combinations are possible.

If this is not the case, at least one of the mechanisms should be newly developed. Based on the gap between the requirements and the gap, argue which mechanism this should be.

Suitable mechanism

3

Define the gap

Define the gap

Since you are reading this chapter, this indicated that no suitable charging and/or mooring mechanism has been found for the specific case. Now it is important to clearly define the gap between the requirements for this case and the existing product. Notice that this are often not just a single requirements, but rather a specific combination of requirements that cause difficulties.
During the iteration of the design circle, various combinations of requirements should have been tried. Apparently all combinations did not result in an of the shelf solution. Define all the combinations of requirements that make this case difficult. Fill out the table on the right page to have a clear overview of the gap(s).

How to continue

With the gap(s) that have been defined, take a last look at the existing products. Which of these products could possibly cover this gap if some modifications where made to the design of the mechanism. For instance: "*This crane solution would be suitable if the tidal difference compensation was increased with two meters*" or *"This charging system would be fitting the case if the power transfer could be doubled".* Try to define this for all gaps.

Now that the issues have become clear and possible solutions have been found, you can get in touch with the suppliers of the system(s) chosen, to collaborate on a new charging and/or mooring system.

Define the gap	
Combination of requirements	
Possible solutions	

A

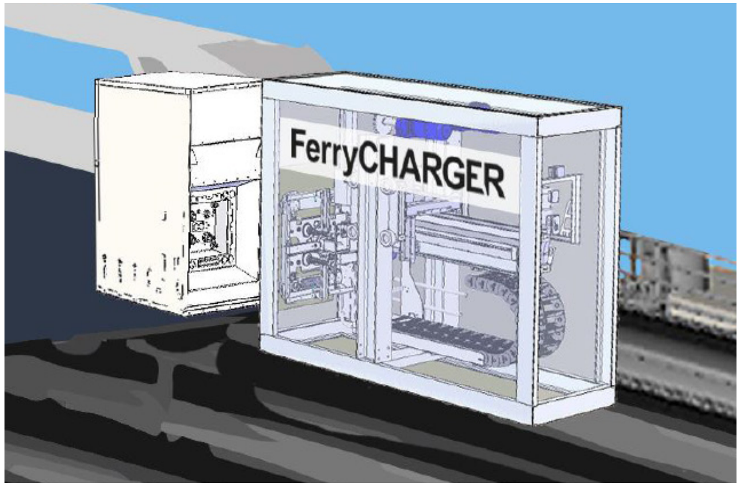
Available charging mechanisms

Charging mechanisms

Cavotec ramp solution

Electricity				
Power [MW]	3.5	3.5	7.5
Voltage [V]	690	1200	11000
Current [A]	4900	3000	660
AC/DC	AC	DC	AC
Dimensions			
Ship unit			
L x W x H [m]	0.55 x 0.225 x 0.55		
Mass [kg]	80		
Shore unit			
L x W x H [m]	1.70 x 0.99 x 0.90		
Mass [kg]	750		
Tidal difference	As high as ramp can move		
Flexibility			
x [± mm]	100		
y [± mm]	100		
z [± mm]	200 - 750		
α [± deg]	3		
β [± deg]	5		
γ [± deg]	5		
Automation	Automated		
Connection time [sec]	ca. 15		
Investment costs [€]	275 000		
Currently used for	None. Prototype phase.		

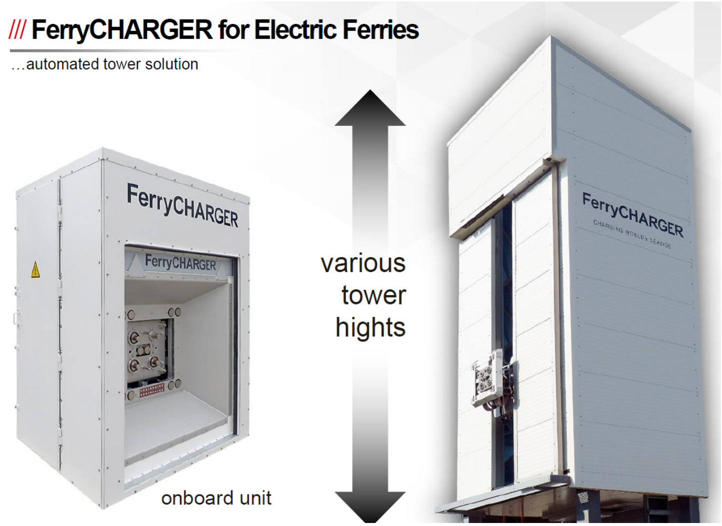
Stemmann-technik ramp solution



Electricity			
	Power [MW]	3	7
	Voltage [V]	1000	11000
	Current [A]	2900	600
	AC/DC	AC	AC
Dimensions			
	Ship unit		
	L x W x H [m]	1.4 x 1.4 x 2.5	
	Mass [kg]	1500	
	Shore unit		
	L x W x H [m]	3.5 x 1.4 x 2.5	
	Mass [kg]	2500	
	Tidal difference	As high as ramp can move	
Flexibility			
	x [± mm]	200	
	y [± mm]	200	
	z [± mm]	700 - 1600	
	α [± deg]	5	
	β [± deg]	5	
	γ [± deg]	5	
Automation		Automated	
Connection time [sec]		ca. 15	
Investment costs [€]		500 000	
Currently used for		None. Prototype phase.	

Charging mechanisms

Stemmann-technik tower solution



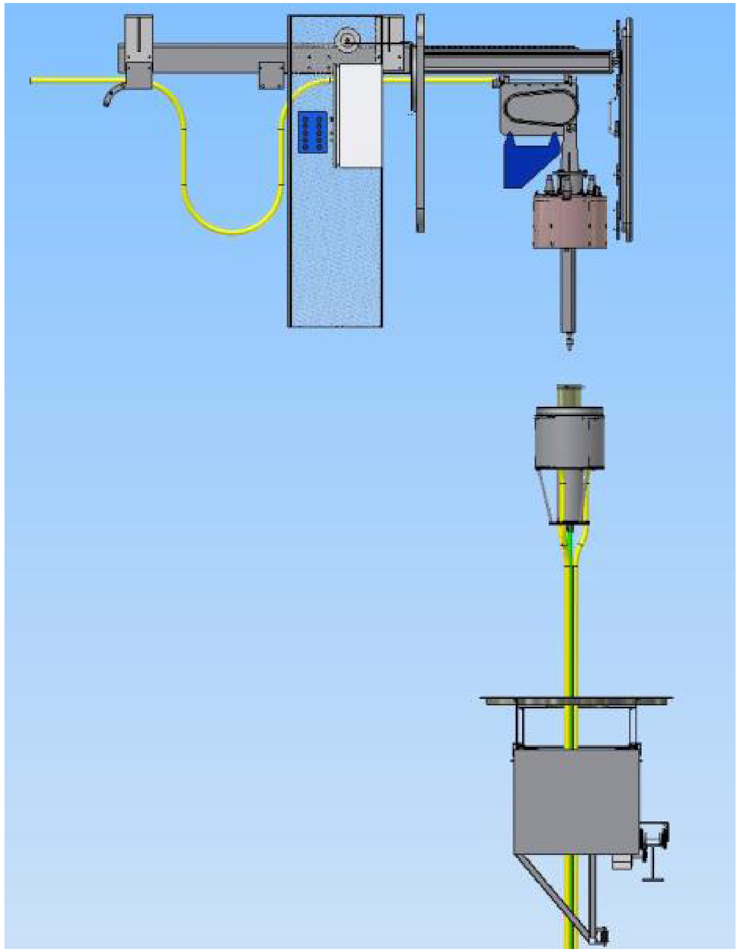
Electricity			
	Power [MW]	3	7
	Voltage [V]	1000	11000
	Current [A]	2900	600
	AC/DC	AC	AC
Dimensions			
	Ship unit		
	L x W x H [m]	1.4 x 1.4 x 2.5	
	Mass [kg]	1500	
	Shore unit		
	L x W x H [m]	3.3 x 4.0 x 11.0	
	Mass [kg]	18000	
	Tidal difference	ca. 4.5m. Can possibly be increased.	
Flexibility			
	x [± mm]	200	
	y [± mm]	200	
	z [± mm]	700 - 1600	
	α [± deg]	5	
	β [± deg]	5	
	γ [± deg]	5	
Automation		Automated	
Connection time [sec]		ca. 15	
Investment costs [€]		750 000	
Currently used for		MF Ampere (NO), Anda-Lote ferry (NO)	

Mobimar Nector

Electricity		
	Power [MW]	4.4
	Voltage [V]	1000
	Current [A]	2800
	AC/DC	AC
Dimensions		
	Ship unit	
	L x W x H [m]	0.75 x 0.70 x 1.2
	Mass [kg]	250
	Shore unit	
	L x W x H [m]	5.5 x 1.5 x 3.5
	Mass [kg]	4500
	Tidal difference	As high as ramp can move
Flexibility		
	x [± mm]	200
	y [± mm]	200
	z [± mm]	700 - 1600
	α [± deg]	4
	β [± deg]	8
	γ [± deg]	4
Automation		Automated
Connection time [sec]		< 30
Investment costs [€]		500 000
Currently used for		E-Ferry, Aeroe (DK)

Charging mechanisms

NG3



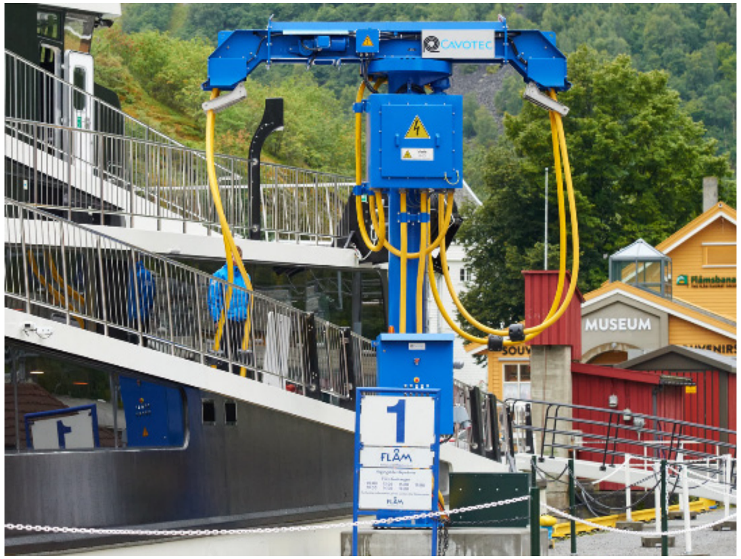
Electricity		
	Power [MW]	Varying from 2.5 to 6.5
	Voltage [V]	11 000
	Current [A]	<600
	AC/DC	AC
Dimensions		
	Ship unit	
	L x W x H [m]	
	Mass [kg]	-
	Shore unit	
	L x W x H [m]	
	Mass [kg]	-
	Tidal difference	
Flexibility		
	x [± mm]	
	y [± mm]	
	z [± mm]	
	α [± deg]	
	β [± deg]	
	γ [± deg]	
Automation		Automated
Connection time [sec]		ca. 120
Investment costs [€]		500 000
Currently used for		Color line, Kristiandsand and Larvik (NO)

Wartsila inductive charging

Electricity		
	Power [MW]	2.5
	Voltage [V]	690
	Current [A]	2500
	AC/DC	AC
Dimensions		
	Ship unit	
	L x W x H [m]	2.8 x 0.7 x 1.8
	Mass [kg]	2500
	Shore unit	
	L x W x H [m]	2.8 x 0.7 x 1.8
	Mass [kg]	2500
	Tidal difference	ca 3. m
Flexibility		
	x [± mm]	0.25
	y [± mm]	0.5 (max distance between plates)
	z [± mm]	0.25
	α [± deg]	*As long as plates do not collide*
	β [± deg]	*As long as plates do not collide*
	γ [± deg]	*As long as plates do not collide*
Automation		Autonomous
Connection time [sec]		Automatic with 75% coverage
Investment costs [€]		1 500 000
Currently used for		MF Folgefonn (NO)

Charging mechanisms

Cavotec manual crane



Electricity	
Power [MW]	0.5
Voltage [V]	400
Current [A]	1200
AC/DC	AC
Dimensions	
Ship unit	
L x W x H [m]	ca. 1 x 1 x 1
Mass [kg]	-
Shore unit	
L x W x H [m]	ca. 2 x 2 x 5
Mass [kg]	-
Tidal difference	ca 3. m
Flexibility	
x [± mm]	ca. 500
y [± mm]	ca. 500
z [± mm]	ca. 1000
α [± deg]	-
β [± deg]	-
γ [± deg]	-
Automation	Manual
Connection time [sec]	120-240
Investment costs [€]	-
Currently used for	Vision of the Fjords and Future of the Fjords (NO)

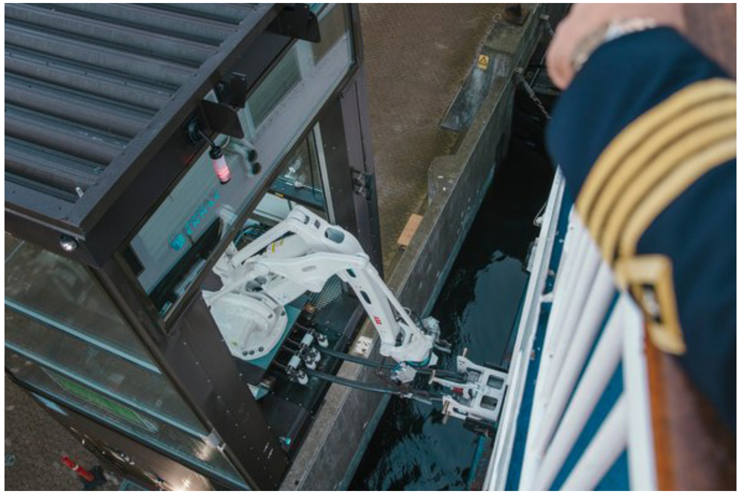
Cavotec Automated Plug-in

Low flexibility with respect to impluse motions, due to large weight of the plug.

Electricity		
	Power [MW]	1.2
	Voltage [V]	690
	Current [A]	1200
	AC/DC	AC
Dimensions		
	Ship unit	
	L x W x H [m]	ca. 1.5 x 1 x 1.5
	Mass [kg]	-
	Shore unit	
	L x W x H [m]	ca. 2.5 x 2.5 x 10
	Mass [kg]	Plug: 800 kg
	Tidal difference	ca. 3m
Flexibility		
	x [± mm]	100
	y [± mm]	100
	z [± mm]	1000
	α [± deg]	-
	β [± deg]	-
	γ [± deg]	-
Automation		Automated
Connection time [sec]		60
Investment costs [€]		-
Currently used for		MF Ampere (NO) and Elektra (FI)

Charging mechanisms

ABB Robot Arm



Electricity		
	Power [MW]	10.6
	Voltage [V]	10 500
	Current [A]	600
	AC/DC	AC
Dimensions		
	Ship unit	
	L x W x H [m]	-
	Mass [kg]	-
	Shore unit	
	L x W x H [m]	ca. 2.5 x 2.5 x 7
	Mass [kg]	-
	Tidal difference	ca. 2 m
Flexibility		
	x [± mm]	-
	y [± mm]	-
	z [± mm]	-
	α [± deg]	-
	β [± deg]	-
	γ [± deg]	-
Automation		Autonomous
Connection time [sec]		ca. 60?
Investment costs [€]		-
Currently used for		ForSea Ferries, Aurora and Tycho Brahe (SE and DK)

Skoon

Skoon is still is development phase and has not been implemented yet in any vessel. Form the knowlegde from other electric vessels, it can be argued that the electric energy stored in one container is approximately 1 kWh.

Skoon is advised consider for relatively large vessels, with a large energy demand and that dock in ports where ship-to-shore cranes are present to replace the containers. It can be especially useful for a fleet of vessels, since the Skoon containers are easily interchangable between vessels, even if the vessel designs are varying.

Stemmann-Technik charging crane

This system is currently developed by Stemmann-technik for a new ferry of Damen. Once this design is finished, this should be included in the guideline to share the knowlegde within the company

B

Available mooring mechanisms

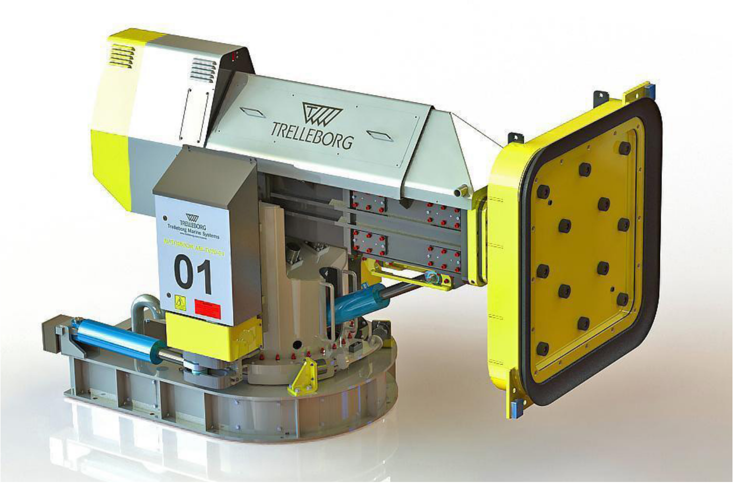
Mooring mechanisms

Cavotec MoorMaster™

Forces[1]		
x-direction [kN]	100	200
y-direction [kN]	200	400
z-direction [kN]	100	200
Dimensions		
Ship unit		
L x W x H [m]	Surface: 1.9 x 1.4	Surface: 4.0 x 1.5
Mass [kg]	-	
Shore unit		
L x W x H [m]	2.0 x 1.7 x 3.0[2]	2.1 x 2.2 x 2.3[2]
Mass [kg]	8 400	15 650
Tidal difference		
Range of motion		
x [± mm]	200	400
y [± mm]	max. 1200 outreach	max. 1500 outreach
z [± mm]	700	100
Automation	Automated	
Connection time [sec]	30	
Investment costs [€]	-	
Energy use [kW]	2.5	5.5
Currently used for	Most used automated mooring system. Multiple systems are installed spread over 80 ports for the mooring of ferries, container and bulk vessels.	

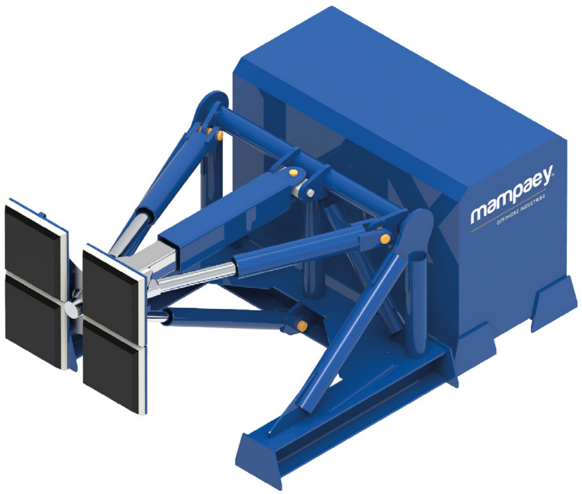
[1]Directions of the forces corresponding to the axis of the vessel that is moored.
[2]Dimensions of the box without the extending arm. So L x W represents the required footprint.

Trelleborg AutoMoor



Forces			
	Holding capacity [ton]	20	40
Dimensions			
	Ship unit		
	L x W x H [m]	Surface: 1.78 x 1.78	Surface: 3.43 x 1.78
	Mass [kg]	-	
	Shore unit		
	L x W x H [m]	3.8 x 1.8 x 2.4	4.1 x 3.4 x 2.5[2]
	Mass [kg]	7 800	11 000
	Footprint [m^2]	5.4	7.5
	Tidal difference	-	
Range of motion			
	x [± mm]	500	500
	y [± mm]	max. 2100 outreach	max. 2100 outreach
	z [± mm]	1000	1000
Automation		Automated	
Connection time [sec]		30	
Investment costs [€]		-	
Energy use [kW]			
	Drive motor	5.5	7.5
	Vacuum pump	1.5	2.5
Currently used for		Not yet used.	

Mampaey intelligent Dock Locking System®



Forces[1]		
	x-direction [kN]	130
	y-direction [kN]	320
	z-direction [kN]	130
Dimensions		
	Ship unit	
	L x W x H [m]	Surface: ca 1.8 x 1.7
	Mass [kg]	-
	Shore unit	
	L x W x H [m]	2.5 x 3.5 x 1.7[2]
	Mass [kg]	5 600
	Tidal difference	-
Range of motion		
	x [± mm]	-150 to +150
	y [± mm]	- 150 to +300
	z [± mm]	-800 to + 800
Automation		Automated
Connection time [sec]		10
Investment costs [€]		-
Energy use [kW]		30
Currently used for		First model has just been installed the Woolrich ferry in London.

[1]*Directions of the forces corresponding to the axis of the vessel that is moored.*
[2]*Dimensions with outreach of arm. So L x W represents the required footprint.*

MacGregor Automooring

Forces		
	Holding capacity [ton]	25 - 65
Dimensions		
	Ship unit	
	L x W x H [m]	
	Mass [kg]	-
	Shore unit	
	L x W x H [m]	
	Mass [kg]	
	Tidal difference	
Range of motion		
	x [± mm]	
	y [± mm]	
	z [± mm]	
Automation		
Connection time [sec]		
Investment costs [€]		400 000 - 500 000
Energy use [kW]		
Currently used for		Ca. 27 systems are installed spread over 9 ports for the mooring of ferries, container and bulk vessels.

[2]*Dimensions of the box without the extending arm. So L x W represents the required footprint.*

Mooring mechanisms

Damen system, Copenhagen ferry

This system is currently developed by Damen to moor a passenger ferry in Copenhagen. Once this design is finished, this should be included in the guideline to share the knowlegde within the company