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Wireless Charging Technology Infrastructure for Ferries in Göteborg (Västra Götaland)

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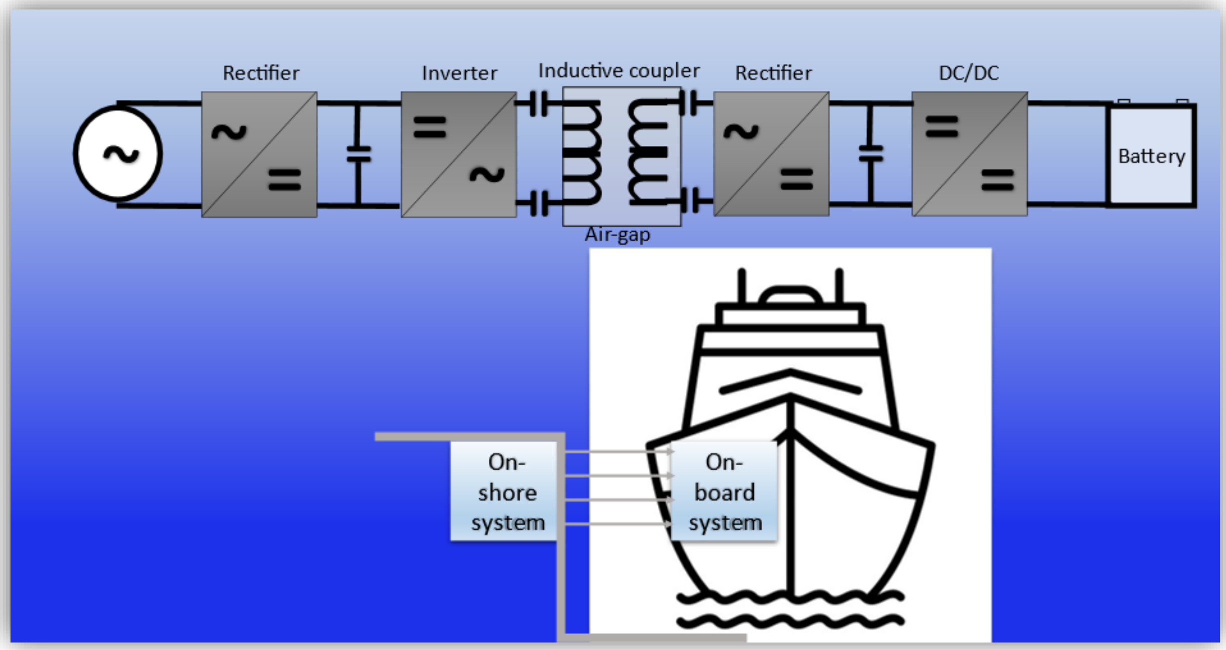

MASTER'S THESIS
Electric Vehicle Engineering
Department of Engineering Science

UNIVERSITY WEST

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Abstract

The maritime transport sector makes a significant contribution to greenhouse gas (GHG) emissions, playing a consistent and increasing part in global CO2 emissions. Electrification of marine transportation is a key and necessary step for achieving the goals of the Paris Agreement and for avoiding the worst consequences of climate change.

Sweden is among the first countries pleading for zero-emission transportation within 2045. However, one of the key challenges facing the widespread adoption of electric boats is the availability and efficiency of charging infrastructure.

Wireless power transfer technology with more focus on inductive power transfer technology in the marine sector was investigated.

The focus is wireless charging infrastructure for passenger ferries in Goteborg. Vesta was the ferry chosen for the case study and it operates on the Saltholmen to Vrångö route. The route, schedule, and ferry energy consumption were investigated to implement the wireless charging infrastructure. Swot analysis was performed to show the strengths, weaknesses, opportunities, and threats of the research. Based on this investigation, the power profile, energy storage, and adopted solution with its system were proposed.

Keywords: Wireless power transfer, Electric ferries, shore infrastructure, swot analysis, electrification, Vesta

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Nomenclature

Glossary

AC	= Alternating Current
AES	= All Electric Ships
AM	= Ante Meridiem
BMS	= Battery Management System
CPT	= Capacitive Power Transfer
DC	= Direct Current
EMI	= Electromagnetic Interference
ESS	= Energy Storage System
EU	= European Union
GHG	= Greenhouse Gases
ICCT	= International Council on Clean Transportation
ICE	= Internal Combustion Engine
IGBT	= Insulated Gate Bipolar Transistor
IMO	= International Maritime Organization
IPT	= Inductive Power Transfer
HES	= Hybrid Electric Ships
HMI	= Human Machine Interface
LIB	= Lithium-Ion Battery
MV	= Medium Voltage
MOSFET	= Metal Oxide Silicon Filled Effect Transistor
NM	= Nautical Miles
OEM	= Original Equipment Manufacturer
PHES	= Plug-in Hybrid Electric Ships
PM	= Post Meridiem
SOC	= State of Charge
VSC	= Voltage Source Converter
WPT	= Wireless Power Technology
ZVS	= Zero-Voltage Switching

Symbols

%	= Percent
Ω	= Ohms

1. Introduction

Global warming problems are not a future problem anymore. Effects that scientists had long predicted would result from global climate change are now occurring, such as sea ice loss, accelerated sea level rise, and longer, more intense heat waves [1].

Fossil fuels – coal, oil, and gas – are by far the largest contributor to global climate change, accounting for over 75 % of global greenhouse gas emissions and nearly 90 % of all carbon dioxide emissions. As greenhouse gas emissions blanket the Earth, they trap the sun's heat. This leads to global warming and climate change. The world is now warming faster than at any point in recorded history. Cutting down forests, manufacturing goods, producing food and transportation are the factors that most contribute to greenhouse emissions.

Most cars, trucks, ships, and planes run on fossil fuels. That makes transportation a major contributor of greenhouse gases, especially carbon-dioxide emissions. Road vehicles account for the largest part, due to the combustion of petroleum-based products, like gasoline, in internal combustion engines. But emissions from ships and planes continue to grow. Transport accounts for nearly one-quarter of global energy-related carbon-dioxide emissions. And trends point to a significant increase in energy use for transport over the coming years [2].

Electrification of transportation is a key and necessary step for achieving the goals of the Paris Agreement and for avoiding the worst consequences of climate change, such as the loss of environmental habitats and the disruption of ecosystems. In the past decade, the need for a sustainable transport system has been raised by civil society and policies [3]

Sweden's vision is to be the first fossil-free welfare nation in the world. The 22 roadmaps for fossil-free competitiveness are the backbone of these efforts, and the purpose of this follow-up is to provide a more detailed picture of actual progress made towards putting them into practice [4].

1.1 Background

With increasing concerns about climate change and environmental sustainability, there is a growing need for clean and efficient transportation solutions. This includes marine transportation, where traditional fuel-based engines can be a significant source of pollution and emissions [4]. The rising shipping transportation caused by the global demand for trading activities implies higher emissions to the environment. Statistics of the seaborne trade from 1990 to 2020 show a drastically increasing trend, almost triple the volume of goods loaded in the port worldwide compared to 1990 [5].

The maritime transport sector makes a significant contribution to greenhouse gas (GHG) emissions, being responsible for around 2.89 % of the global CO2 emissions and for approximately 13 % in the European Union (EU) [6].

In response to this need, there has been a growing interest in electric and hybrid electric boats. However, one of the key challenges facing the widespread adoption of electric boats is the availability and efficiency of charging infrastructure. This is particularly for marine vessels, which often have unique charging requirements and may be used in a variety of different environments [7].

Shore-to-ship charging technologies involves such as conductive/wired charging and wireless charging systems. This system must meet power system requirements by having a step-down transformer, energy storage systems (batteries), power electronics converters for AC/DC and DC/DC conversions, transformers to maintain galvanic isolations, voltage level adjustment, circuit breakers, and cable management systems.

1.1.1 Conductive Charging

Conductive charging can be classified as AC or DC, depending on the type of electric connection between the shore and the ship. The AC system transfers the energy to the ship via an AC connection which requires an AC/DC converter to be installed on-board. Passenger and/or car ferries require higher power, and a larger and heavier AC/DC converter is required [8]. Therefore, a dedicated infrastructure is required that can align with the requirements of the ship's battery management system (BMS).

Smaller boats use the standard 3-phase 400 V AC plug for shore charging because it's the most used charging solution. Hence, they can enjoy the luxury/ comfort of having the availability of a 400 V AC source.

DC fast chargers typically have two power conversion stages: a three-phase AC/DC rectifier with power factor correction and a DC/DC converter. This charging method is not limited by the power of the on-board charger and can therefore be much faster. Both AC and DC charging is using these two power conversion stages, with the difference that for AC charging these are located inside the on-board charger which is located inside the vessel. For DC charging these are located inside the DC charger which is located outside of the vessel.

Although conductive charging offers the advantages of faster and more efficient charging as well as the reliability of an established technology, concerns regarding safety and infrastructure cost, especially for larger ferries, need to be addressed. Conductive charging also requires that the ferry remains stationary while charging, leading to a reduction in range and flexibility.

Overall, conductive charging can be an effective solution for ferries with predictable routes and schedules, but it might not be ideal for vessels that require more flexibility or have limited time for charging.

The limitations of conductive charging power levels are limited by the weight and size of charging cable connectors, voltage, and charging equipment current rating. The weight and size are directly affected by the power level requirements. In practice, a higher power level will increase the weight and sizes of the charging components which is impractical for use in boats with weights and space constraints.

Furthermore, conductive charging could increase stressful environment as laying cables on the floor pose safety issues. There is also a risk that the connectors will be worn out and corroded after a while, which will lead to increased resistance causing a temperature rise in the connector. It can also lead to bad connection resulting in communication issues when using a charging standard such as CCS. In addition, there is also a risk of having dirt, salt, etc. in the inlet which can also cause issues. The cable itself can also be extremely dirty which might be inconvenient for the user, especially for private people.

1.1.2 Wireless Charging

Wireless charging, also known as inductive charging, removes the need for plug-in charging, the transfer of the power from shore to the vessel takes place through two spaced coils. The transmitter coil is powered through power electronics converter, which provides high-frequency current and a high-frequency field that couples with the receiver coil and allows the wireless transfer of electrical power. A downstream rectifier converts the signal to DC current that allows the battery to be charged.

The absence of electrical contact between the two parts of the system increases remarkably the safety of the operation as no human interaction is required; also reduces the typical problems such as erosion and corrosion due to the saline environment, thus with less maintenance required, the cost is further lowered, and the life cycle of the system increased [8], [9]. Galvanic isolation is also inherently provided between the charging equipment on land and the on-board electrical system [10].

In addition, wireless charging avoids extra challenges with the plug-in cable approach which can be complicated by the continuous movement of the ferry and/or weather conditions.

The major weaknesses of wireless charging are [9]:

- Efficiency: wireless charging systems are not as efficient as conductive charging, meaning that more energy is lost resulting in higher costs.
- The initial increased cost of installing the infrastructure, and probably, more additional equipment such as power amplifiers and control units.

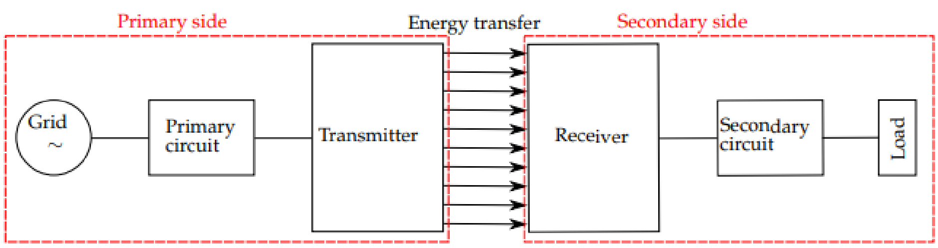

Figure 1: Wireless charging schematic [11]

The wireless charging power is limited by the losses in the primary circuits, which convert DC to high-frequency AC. It is also limited by the power transfer between the charging pads and the receiving coils although less, depending on how good the design of the coils is. On the secondary side are also losses occurring in the rectifier stage.

Although charging is mainly dependent on the power and to some extent the losses, the efficiency is typically lower than that of conductive charging. It ranges between 86% and 90% [3], resulting in more energy loss during the charging process. This leads to range reduction and longer charging for electric boats. Charging pad distance, alignment, and charging coils size influence the maximum power level that can be achieved.

High power levels can generate heat and electromagnetic interference which pose safety risks to humans. This applies to both the conductive and inductive charging of electric boats. However, for inductive charging, there is a higher risk of having high leakage fields which can induce currents close to metal objects.

1.2 Problem Statement

Boats in the Göteborg area rely on traditional fuel, which is an unwanted contribution to the total greenhouse emissions. A total energy transition is required in the maritime industry, as the target roadmap requires a 70 % reduction in greenhouse emissions by 2030 and zero emissions by 2045.
To tackle these issues, electrification is one of the possible solutions [4].

The main challenges of marine electrification are related to the limitations of current battery technology, the need for charging cables, longer distance operations, and the economic challenges associated with implementing the necessary infrastructure and changing energy consumption behavior.
Currently, ferries require frequent docking and manual connection to a power source, which can be time-consuming and disruptive to their schedules. Hence, wireless charging technology could address these issues by allowing ferries to charge their batteries while in transit, reducing downtime and improving their environmental impact.

1.3 Research Purpose

The project aims to facilitate the process of electrification of the marine industry by investigating the wireless charging infrastructure for ferries as a way of easing the operations of charging and improving their efficiency and sustainability.

1.4 Research Questions

- What are the existing technologies for wireless charging, their power ratings, and power limitations?
- Can wireless charging be a preferred solution instead of conductive charging?
    - Does wireless charging solve the corrosion problem of conductive charging?
- What are the required power ratings needed to implement/adopt wireless charging infrastructure on route 281 operating in Göteborg harbor?

1.5 Research Scope

The thesis scope is to investigate wireless charging technology with the focus on the opportunity of electrifying ferries in Göteborg.

Investigate the state of the art of wireless charging technology for waterborne transportation.

The thesis will have a qualitative approach based on the literature study and the content analysis of the power profiles and battery capacity of the existing vessels operating in the harbor of Göteborg.

1.6 Thesis Outline

The thesis will be structured into 6 sections. The first part is the introduction part which deals with the current situation, research purpose, and scope. The second chapter is about thesis theories and research framework. The third chapter discusses more in-depth the charging methods and existing standards. The results will be shown in the fourth section while the fifth chapter discusses the previous one in-depth. Conclusions and future research will be in the last chapter.

2. Methods

2.1 Research Methodology

The chosen methodology, strategy, data collection, and analysis for this research will be discussed.

2.1.1 Research Approach

Considering that wireless charging for ferries is a relatively emerging topic, an abductive research method is best fitting for this, and it is a combination of inductive and deductive. Inductive research is based upon qualitative data collection and the subject unfolds during the development and research process [12]. While the deductive approach is structuring the research strategy and analysis based upon the current theory [13].

Interpretivism research philosophy that allows the researcher to understand the clear link between the research subject and the researcher, which implies that people cannot be separated from their knowledge was adopted for this research [13]. This is qualitative research that allows the researchers to be referred to as primary data instruments to perform interviews, observations, and documentation as data collection methods [14]. Hence the researchers in this project will be used as instruments to explore, use personal analysis, and make meanings of events.

This research is a single and holistic case design. This is because a single and holistic case study provides an opportunity to test and analyze a phenomenon that few have studied before which makes it well suited for this research [12]. The use of case studies in the research design gives the opportunity to know in advance what data to gather and the appropriate analysis methods to answer the research question [15]. The research will be co-produced by engaging the stakeholders (academia and industrial) in several stages of the research [16]. Open-minded "how" and "why" questions from an explorative standpoint will be used to help the researchers to reflect constantly and explore the answers to the research question [12].

2.2 Data Collection

To capture the research questions, the data will be collected through various primary and secondary data collection means. These methods will be used to collect and create orderliness to the data so they can answer research questions.

2.3 Literature Review

The research began by collecting secondary data resources to increase the view on wireless charging for ferries in the marine industry. A systematic literature review is used to acquire secondary data. Scientific research databases such as University West Library, Scopus, Science Direct, and Google Scholar will be used to acquire these secondary data.

The first ship using batteries was built in 1839 its duty was to convey passengers in St. Petersburg [17], [18]. The Eureka boat was built in 1881 and was powered by lead-acid and was designed by Gustave Trouve [18]. This shows that the propulsion of ships by using batteries and electrical equipment is not a novel concept. the first known diesel-electric vessel was launched in 1903 into the Russian River tanker Vandol [19]. In the early twentieth century saw a reduction in battery power source propulsions for ships due to the introduction of the internal combustion engine (ICE) [17]. The fast development of larger ICE in mechanical power trains and efficiency quickly phased out the use of electric propulsion systems in civilian transports after World War II. Diesel-electric propulsion came back into use in the year 1980s [19].

The energy crisis during the 1970s brought about the need to research hybrid drivelines in the maritime industry. Norwegian vehicle transport ferry Ampere, which has a complete battery-based energy system, was introduced in 2016 alongside diesel-electric ferries, mechanical propulsion aided by electricity, and solar panels car carriers storing energy generated in batteries.

To achieve reductions in greenhouse gas emissions in the maritime sector, electrification of vessels needed to be incorporated to increase functionality, flexibility, and fuel efficiency [20]. The major benefits of battery-powered ferries are that it is less dependent on fossil fuel and no emission during travel time. The International Maritime Organization (IMO) recommended the development of electric ferries and harbor charging stations to exploit renewable energy sources to mitigate polluting urban coastal areas with emissions [21].

Nowadays, several companies such as Wartsila, ABB, and Cavotec have managed to provide some solutions to/for transitioning into clean energy alternatives for ferries. These mentioned companies have developed specific battery charging and mooring systems for electrical ferries [21]. There are some limiting factors such as the system complexity, lack of charging infrastructures, long charging time, costs, grid supply conditions, and standardizations. These factors inhibit the vast adoption and diffusion of electric ferries in society. The details including power trains, battery type, capacity, speed, vessel length, year of manufacturing, etc., are some of the deciding energy and power usage in the vessels. The ships can be divided into three which are based on their propulsion types, the AES (All Electric Ships), Hybrid Electric Ships (HES), and the PHES (Plug-in Hybrid Electric Ships) [22].

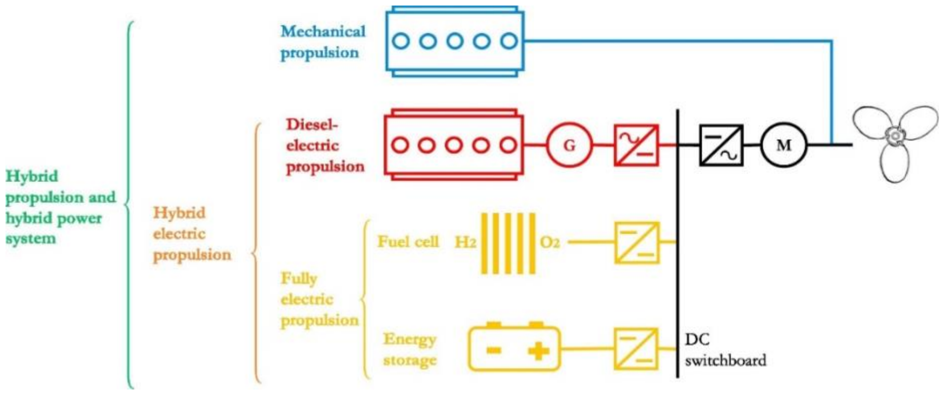

Figure 2: Propulsion systems [23]

HES has two main propulsion systems which are battery-powered electric motor and the ICE. External power sources, or other drivelines can be used to charge HES batteries and the fact that ship's batteries can only be charged via the other driveline differentiates electrical hybrids. Currently in Göteborg, the Elvy hybrid ferry owned by Västtraffik is an example of a diesel-electric propulsion system [24]. Energy efficiency can be improved with hybrid powertrains in ships. Several factors determine ICE performance such as speed, and engine load, and while in hybrid systems, the battery can help the ICE to achieve its maximum output efficiency [25]. The advantages of implementing electric and hybrid propulsion over ICE propulsions in ships/ferries are highlighted in the figure below.

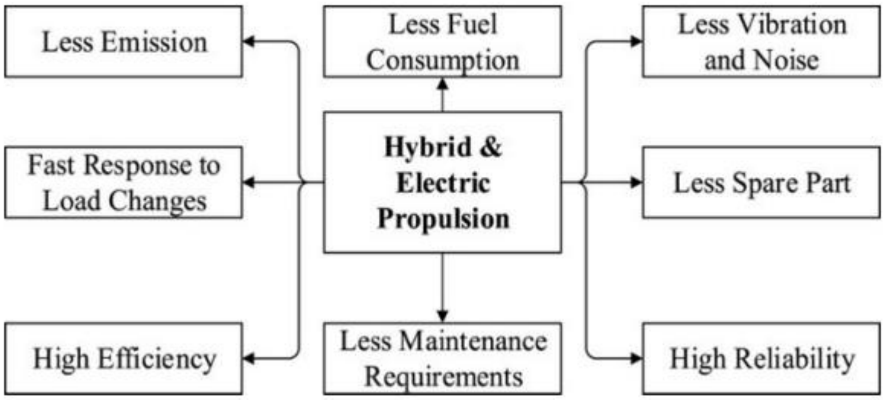

Figure 3: Advantages of electric and hybrid propulsion [23]

The figure shows that there are fewer emissions and high efficiency from the energy storage system (ESS) and boat weight is also dependent on ESS installed in hybrid propulsion systems. This helps to handle peaks in demand when the ferries generators are running and not do, they only provide supply to the propulsion system, but they also charge the batteries [26]. When ferries generators are at rest, the inverter stage of the AC drive can draw power from the batteries to operate the electric propulsion motors when the ferries generators are not running. This immediately benefits the ferries operating at low speeds during maneuvering at the harbor which reduces the need to run the diesel engines, resulting in fuel savings, being environmentally friendly, and battery power supply to the ferries. Some harbors have restrictions regarding combustion engines, therefore electric propulsion is necessary when operating in or nearby these harbors [27].

AES provides a carbon-free operation solution to the maritime industry, but AES's drawbacks are that it is more expensive, longer charging time, and heavier because it requires larger battery packs than hybrid ferries.

The designing of charging infrastructure for maritime industry vessels depends on several factors such as charging needs, battery size, number of stops, timetable, route length, docking method, grid strength, and supply conditions [28].

Shore Infrastructure

The electric ferries port charging station encompasses a step-down transformer connected to the MV grid, power converters for AC/DC conversions, transformers to maintain galvanic isolation and adjust the voltage levels, HMI, circuit breakers, ESS and cable management systems [8], [29].

2.3.1 Charging WPT Technologies in the Marine Environment

The wireless power transfer (WPT) technology has its beginning in the 19th century when Nicola Tesla introduces the transmission of electric energy from a power source to an electric equipment through a non-contact medium such as an electric field, magnetic field, electromagnetic wave, laser, and acoustic wave without wires.

The most important advantage of the WPT technology is eliminating the rigid physical connection between the shore and the ship side offering at the same time the possibility to resist misalignment due to the continuous and random movement of the ship.

Good electrical isolation can be achieved thus, major safety and reliability of the system. WPT offers more flexibility in the layout of the system and reduces considerably the maintenance interventions.

One of the most important aspects of the WPT technology is the complete elimination of the leakage caused by conductor exposure, highlighted by the working environments of the ships: high humidity levels and saline.

According to the transmission principle, the current WPT technology used in the shipping field can be divided into electric-field coupled WPT and magnetic-filed coupled WPT [30]

2.3.1.1 Electric-Field Coupling

Electric field coupled WPT or capacitive power transfer (CPT), transmits wireless power through electric fields. High-frequency alternating current induces an electric field between the transmitting plate and the receiving plate.

Studies conducted [31] have shown that CPT underwater could represent a viable solution as it reduces the area occupied by the shore power equipment.

Figure 4 illustrates the underwater power transmission through CPT and its topology.

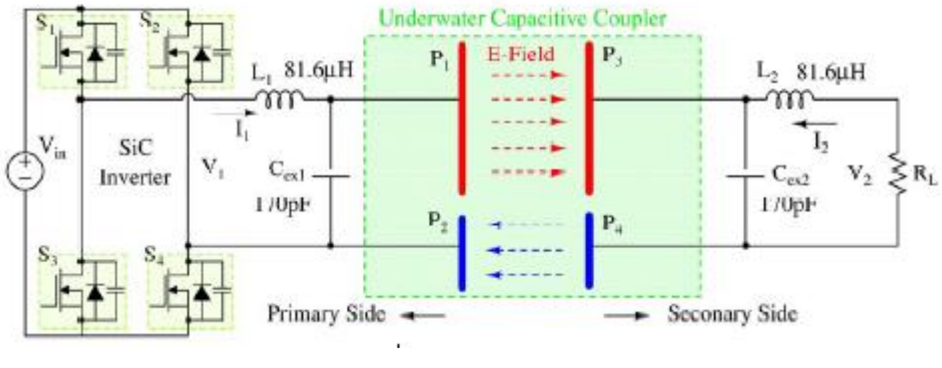

Figure 4: Power transmission through CPT [31]

In the same research conducted [31] the total efficiency of the circuit is about 60.2 % (the transfer power value is 226.9 W across 500 mm distance, input voltage of 100 V, and load resistance of 37.5 **Ω**), a value that needs to be further improved for further applications that aim to high-power applications.

Second research conducted by the Arctic University of Norway [32], proposes the same CPT technology for smaller vessels. The efficiency, in this case, reaches 95 %, maximum power required is 174 kW, but the system should be verified experimentally with further investigations regarding the EMI.

2.3.1.2 Magnetic-Field Coupling

Magnetic-field coupling, or inductive power transfer (IPT) is a system that uses coils and near-field magnetic coupling for power transfer.

The figure below shows the circuit representation of the wireless IPT system.

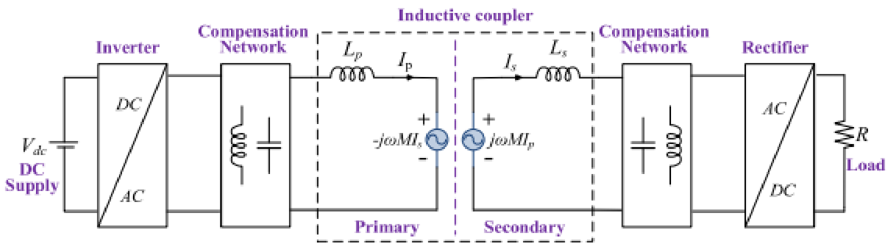

Figure 5: Circuit representation of wireless IPT system [33]

Considering the constraints of energy conversion efficiency, transmission distance, and other factors, IPT technology is mainly adopted currently.

Currently, three main charging systems have been adopted: a fixed system, a mobile, and a multi-degree-of-freedom wireless power supply.

The shore IPT device developed by IPT-Technology is fixed because the transmitter coil is fixed, allowing the power receiving terminal to dock with the shore power supply terminal, suitable for inland ships. Wartsila, in collaboration with Cavotec developed a mobile system, the world's first integrated inductive wireless charging automatic mooring system, that offers the advantage of greater flexibility and application range. The system can compensate for the water level differences caused by tidal motion and begins charging when the gap between the transmitter and receiver coils reaches a certain distance.

A third system is currently proposed, a multi-degree-of-freedom wireless power supply with a charger manipulator able to provide a real-time connection with the receiving terminal and effectively restrain environmental interference [30].

The main drawback of the WPT is the lower efficiency compared to the conductive method. In order to improve the efficiency of wireless charging, the following approaches can be considered: reduce the distance to an optimal designed solution, optimize coil design, ensure proper alignment, increase frequency as well as using new materials such as high-power semiconductors, e.g., silicon carbide, as they allow to use high voltage, higher temperature, and higher switching frequency [34].

Other methods have been studied, [35] proposes a novel system configuration that adds an active power source to the receiver of the wireless charging system. The experimental results show an increase from 84.9 % up to 95.7 % in uncoupling and slightly detuning working conditions.

Further studies conducted by [36] highlight that more efficiency and less electromagnetic interference can be achieved if zero-voltage switching (ZVS) of all metal-oxide silicon-filled effect transistors (MOSFET) switches can be insured. However, this solution necessitates auxiliary DC/DC converters and additional resonant components that increase the cost and system complexity.

Table 1 synthetizes the main characteristics of the WPT for the existing solutions presented earlier [37].

Table 1: Main features of WPT

	CPT	**IPT**
Power range	up to few kW	up to hundreds of kW
Frequency range	1 kHz - 20 MHz	20 - 200 kHz
Operating distance	mm - tens cm	0 - 50 cm
Efficiency	up to 93.4%	up to 98 %
EMI	low	low
Size	m^3	cm^3 - m^3
Safety	Electric field emission. Necessity of appropriated insulation	Safe

2.4 Primary Data Collection

The technical specifications to determine the power profiles for the chosen ferry will be obtained directly from the operating company Styrsöbolaget, and existing internal documents from Volvo Penta.

2.5 Data Analysis

SWOT analysis (strengths, weaknesses, opportunities, and threats), is a basic principle rooted in the strategy making whose goals is to align the company's internal resource capability (a balance of resource strengths and weaknesses) and its external environment factors (market opportunities and profitability and competitive standings) " [38]. Hence, the company's strengths should be utilized to exploit market opportunities and not to cover its weaknesses or fight the threats. The weaknesses and threats should be eliminated and avoided.
SWOT analysis was used in the analysis part of the research (wireless charging technology for ferries in Göteborg) based on the literature review results and from the data outcomes acquired from the case study.

2.6 Research Quality

The quality of the research, reliability, and validity will be used to evaluate the research quality [12], [39]. Academia in the electric vehicle industry and marine industry manager and Styrsöbolaget will be asked for the validity of the data generated.

3. Shore Charging Types and Standards

From a power system point of view, a solution for supplying power from the shore consists of an interface to the main grid by a step-down transformer, possibly an onshore energy storage system typically based on Li-ion batteries (as an option to meet the power requirements if the AC supply at the shore is limited), power electronics converters responsible for AC/DC and DC/DC conversion, transformers for maintaining the galvanic isolation as well as voltage level adjustment, circuit breakers, and cable management system [8].

The charging solution can be divided into AC charging systems and DC charging systems.

3.1 AC Charging

AC shore-to-ship charging topology requires an AC/DC converter placed on-board, similar to the on-board charger used in electrical vehicles. For small leisure and fishing boats, a normal three-phase 400 V AC plug is the common solution, widely available, and will provide more availability for shore charging, therefore, the beneficiaries will not suffer any limitations on their routes as this solution is commonly available in industrial environments. On the other hand, ferries require more power to recharge the on-board batteries, the required power rating of the port charging infrastructure must be designed based on the number of vessels transiting in the harbor, and their on-board battery capacity.

Figure 6 shows an AC shore charging power system connecting to a single-bus DC hybrid on-board.

As a means to ensure redundancy, ferries, and larger vessels are designed to have two or more buses operating in parallel, the below schematic illustrates for simplicity just one bus.

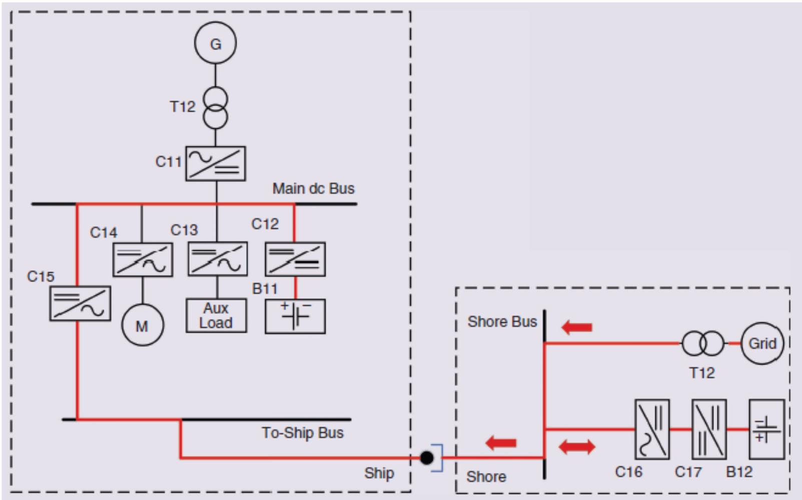

Figure 6: AC shore charging system [8]

T12 is a 50 Hz transformer that steps down the grid voltage into the shore bus and isolates galvanically the shore bus from the grid. Converters C12, directly connected to the on-board battery, and C17, which controls the power of the onshore battery, converts the energy from the shore, and controls the transferred power during the charging and discharging process and the power of the onshore battery. C16 acts as a rectifier during the onshore battery charging process but also as an inverter during on-board battery charging. C15 acts as a charger and rectifies the energy received from shore. For multibus propulsion systems, converters like C15 should be assigned to each bus in order to control the charging power balance of each battery pack.

The same AC shore charging can be connected to an AC-based propulsion system, if an AC-based propulsion system is used instead of DC, then it can be directly connected. For an AC-based propulsion system, it is necessary to synchronize the on-board power of the voltage, phase, and frequency before connecting to avoid inrush currents. The synchronization requires time, therefore, the AC charging for an AC-coupled on-board system is not considered a good solution, especially for fast charging. To ensure galvanic isolation, an additional on-board transformer is installed leading to a higher cost of the system and lower efficiency.

The main battery charger can be installed on-board or off-board, in a dedicated charging station. On-board offers the advantage of easy charging by using a regular AC plug but, due to the limitation in size, weight, and cost, reduces the charging power.

3.2 DC Charging

Figure 7 below depicts a simplified model of a DC shore charging system connected to a DC main bus, but also the same shore configuration can be connected to an AC-based hybrid propulsion system.

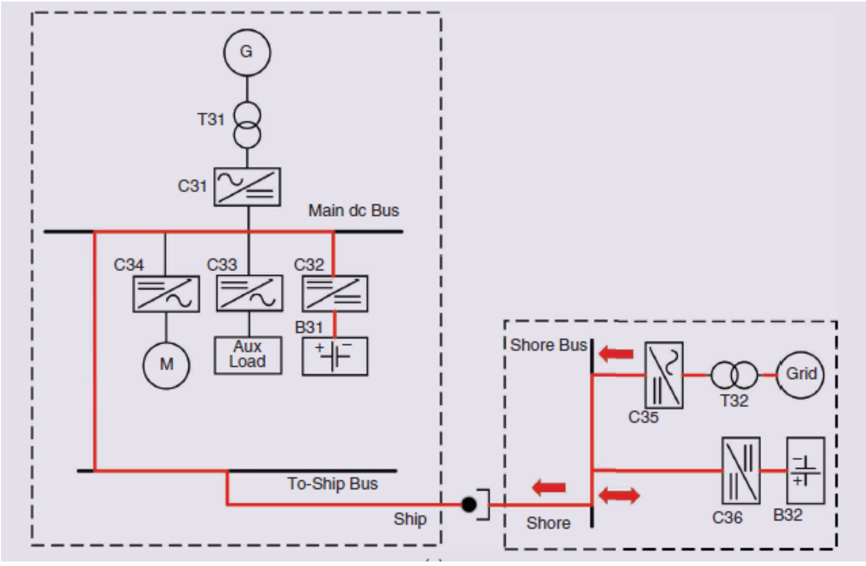

Figure 7: DC shore charging system [8]

Compared with the previous AC system, the on-board converter C15 can be eliminated and replaced by the C35, onshore converter. Their ratings can be different therefore their cost and efficiency may differ. One way to reduce further the weight on-board is to eliminate the charger converter C32, connecting the DC/DC converter directly to the plug and used for controlling the charging power. A junction box is normally used with contactors to disconnect the inlet from the traction voltage bus to avoid hazardous voltage in the inlet every time the batteries are connected.

3.2.1 DC Inductive Charging

Figure 8 below shows a simplified model of inductive charging for a ship with a DC main bus.

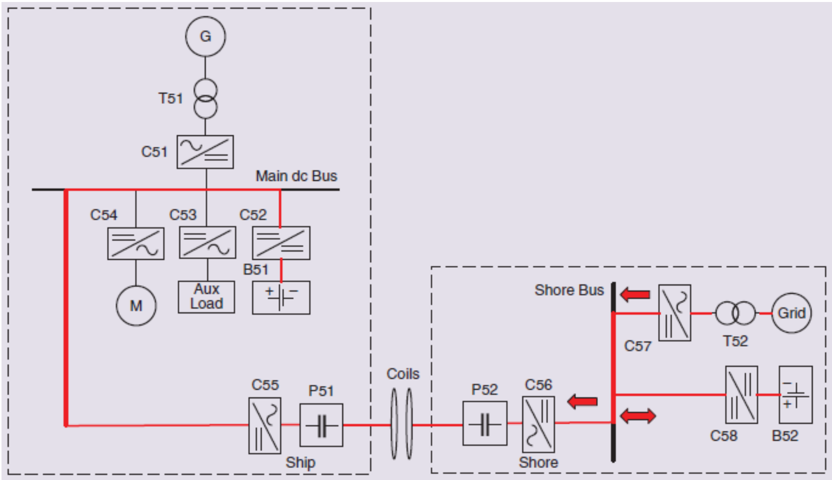

Figure 8: DC inductive charging with main bus [8]

The transmitter and receiver coils act like a transformer with a low mutual inductance. Low magnetic coupling results in a high magnetizing current, therefore capacitive compensation network, P51, and P52 are used for generating the reacting power consumed by the coils. C56 is a high-frequency converter generating square-wave voltage for the transmitter coil. C55 rectifies the high-frequency output of the receiving coil. C55 and C56 can be replaced by a two-level voltage source converter and a diode rectifier. The transmitting and receiving coils provide galvanic isolation, thus, no need for the on-board transformer [8].

3.3 Existing Standards

Standards aim to facilitate collaborative problem-solving, uniformity, and transparent ways of integrating feasible solutions between different actors/suppliers to a reoccurring problem. Usually, a standard is voluntary to apply but it serves as high quality that is conformed with by most actors. However, it may be challenging to unite several disciplines, roles, and countries during the development of standards. There are charging standards when it comes to the electric road vehicle domain but currently, there are only a few for the marine sector and still under development.

Charging Standards in Electric Road Vehicles Domain

The standards in the EV sector address both the charging device and the communication between the EVs and charging devices. In simplicity, the standards primarily address devices that are in the vehicles while the other standards address what is outside the vehicle. Different EV standards are illustrated in Figure 9 below.

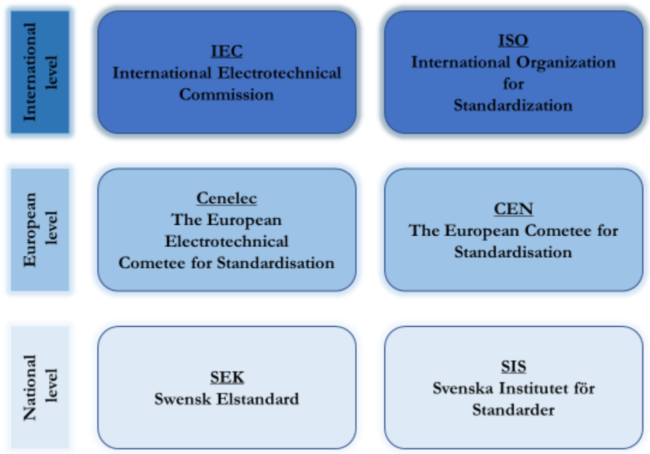

Figure 9: Examples of standards related to charging infrastructure in the EV sector.

Standardization is the process of developing standards based on consensus between several actors (e.g., users, governments, companies, and interest groups) [40]. The Combined Charging System (CCS) was developed by CharIN [41] to test new charging technologies, improve interoperability, and align several actors around a common charging system for both marine and road EVs.

Charging Standards in Marine Sector

Shore-to-ship battery charging can be done by AC or DC and either by conductive or inductive charging. Since 2014, technical standards AC shore-to-ship connection standard 80005-1 for HV have been compulsory within the EU according to Directive 2014/94/EU [42]. While there are no marine DC shore-to-ship connection standards [27] but the international electrical vehicle charging plug standards for AC and DC have been applied depending on the vessel's power demand. The technical standards IEC/IEEE 80005-1 for shore power high voltage levels standard are 6.6 kV and 11 kV and IEC/IEEE 80005-3 for low voltage levels are 400 V, 440 V, and 690 V respectively.

SAE TIR J2954/2 [44] wireless power transfer and alignment for heavy-duty applications; defines new power transfer levels in the higher power ranges needed for heavy-duty electric vehicles. It addresses the unidirectional power transfer, from grid to vehicle; bidirectional transfer may be evaluated for a future document. It is intended for power transfer in vehicles when not in motion, meaning that it should be used in stationary applications and some dynamic applications. It covers requirements needed for safety, performance, interoperability, and methods for evaluating electromagnetic emissions.

4. Results

This chapter comprises of the information received from ferry operator Styrsöbolaget; we proceeded by calculating the needed power profile for the case study. Also, the results from this research will be compared with previous research conducted by Volvo Penta. Furthermore, a systematic literature review of the existing charging solution was considered with respect to our thesis power profile requirements.

4.1 Case Study Ferry "VESTA"

Vesta is a passenger ship, and it is owned by Västtraffik and operated by Styrsöbolaget in the Göteborg harbor area.

Vesta has a capacity to accommodate about 447 passengers as of today, which is the same capacity as when it was first built. There are 246 seats in the saloons, inclusive 68 in the upper deck café. It has a length of 34.42 m and an 8.02 m width respectively.

Figure 10: VESTA [45]

Vesta was built by Båtservice Holding A/S, Norway, delivered in 1998 to AB Göteborg Styrsö Skärgårdstrafik and has been in traffic in the Göteborg's southern archipelago.

Vesta is equipped with two Volvo Penta D13 MH engines each with crankshaft power of about 450 hp and having a maximum speed of 13.5 knots. The exhaust gases are cleaned by the catalytic converters equipped to the main engines.

4.1.1 Route and Timetable

The route between the island Vrångö to Saltholmen at the mainland is chosen for evaluation and it operates on a travel distance of 8 NM, approximately 14.816 km. The trip departs from Vrångö and sails for about 16 minutes before stopping at Donsö for about 5 minutes before sailing for 3 minutes to Styrsö Skäret with a stop of less than 1 minute. From Syrsö Skäret it takes a 10 mins sail to Styrsö Bratten with 3 minutes stoppage time and then continues towards Köpstadsö for about 10 minutes and stops for 3 minutes. The journey between Köpsadsö and Asperö Östra lasts for about 6 minutes with a stopping time of less than a minute before an 8-minute sailing time to Saltholmen where the ferry docks before sailing back towards Vrångö again. The total round trip travel distance is 16 NM (29.63 km) which is about 110 minutes of travel time during the winter timetable schedule.

Figure 11: Route 281 [46].

The Vesta ferry is also known as the line 281 ferry which departs from Vrångö at 12:25 PM and ends at 19:01 PM in Saltholmen on weekdays. Operating hours during the weekend are a bit different from the weekdays, it starts at 14:23 PM till 21:27 PM on Saturdays and between 13:10 till 19:25 PM on Sundays. Kindly note that the same Vesta ferry also services the other travel routes such as 282, 283, and 284 lines. The focus was on route 281, without considering other routes due to time constraints and unavailability of data. The timetable with docking intervals is provided in the table below Table 2.

Table 2: Vesta ferry timetable

Stops	**281**		
Salthomen	11.20	13.25	21.50
Asperö Östra	11.29		
Köpstadsö	11.39	13.40	22.05
Styrsö Bratten	11.44	13.46	22.11
Styrsö Skäret	11.55	13.57	22.22
Donsö	12.00	14.02	22.27
Kårlhomen			22.23
Vrångö	12.22	14.16	22.44
Vrångö	12.25	14.20	22.45
Donsö	12.40	14.42	
Styrsö Skäret	12.43	14.45	
Styrsö Tången			23.19
Styrsö Bratten	12.55	15.00	
Köpstadsö	13.00	15.05	23.30
Asperö Östra	-	15.14	
Salthomen	13.17	15.18	23.47

The docking times are not consistent with less than a minute docking till about 5 minutes. The study proceeded to analyze the data from Styrsöbolaget on Vesta, showing the traveling time from 14:20 PM to 15:18 PM.

4.2 Power Profile for a Roundtrip

Based on the fuel consumption profile graph provided by ferry operator Styrsöbolaget which cannot be published, the mechanical power was calculated for the ferry travelling from Vrångö to Saltholmen.

Considering the energy content of diesel fuel about 9.96 kWh/l and the estimated efficiency of the engines that equip the vessel is about 40 %. Based on the consumption extracted from the provided graph, the power profile of the one-way trip from Vrångö to Saltholmen is shown in Figure 6.

Based on the similar graphs and measurements previously analyzed internally in Volvo Penta, it was assumed that the measurements are made during wintertime, travelling upstream.

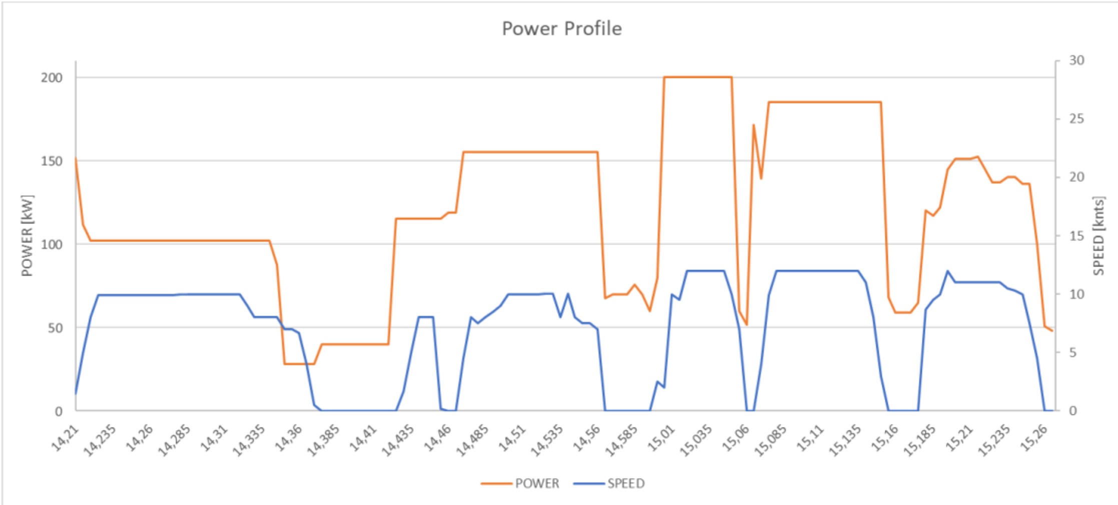

Figure 12: Power Profile for Vesta for a roundtrip

The electrical power profile is based on typical average efficiencies of 95 % for the battery, inverter, and electrical machine.

The total energy consumption for one round trip is approximately 123 kWh, excluding the parasitic and hotel loads. Hotel loads are the sum of heating, air conditioning, lighting, water, and sanitary. For parasitic loads, we should consider pumps, fans, and other auxiliary equipment vital for the operation of the vessel. Based on internal estimated data from Volvo Penta, table 2 below summarizes the supplementary energy consumption for both parasitic and hotel loads.

Table 3: Auxiliary loads

Hotel loads, total for vessel	Unit	Min load, 100%	Max load, 100%
24 VDC Central control cabin floor	kW	0.008	0.030
24 VDC Central control cabin	kW	0.8	3.0
230 VAC Central control cabin	kW	3.5	13.9
HT 230V	kW	1.3	5.0
HT 400V	kW	6.0	23.9
Heat	kW	4.1	16.5
Total	**kW**	**15.6**	**62.4**

Based on the above values we can estimate that the average energy consumption for one round trip is about in the range of 262 and 310 kWh. The maximum value considered for the calculation is 310 kWh.

The number of round trips during one day can be approximated at six: three for the chosen route (one round trip equals 16 NM) and the equivalent of another three (one round trip is 4.86 NM) as the same boat is operating on other shorter routes, thus, the total power needed is:

$$6 \times 310 \text{ kWh} = 1860 \text{ kWh}$$

Volvo energy-optimized battery pack has a capacity of 66 kWh, and assuming that we can utilize 70 % state of charge (SOC) window (between 90 % and 20 % SOC) then 46.2 kWh per battery is available. To supply 1860 kWh, 41 battery packs would be needed to cover 6 round trips. The total weight of the battery will exceed 21 tonnes, therefore fast-charging along the route should be taken into account.

In order to complete one round trip with one charge, 7 to 8 battery packs will be needed for a total of 369.6 kWh (approximately 4.3 tonnes).

Table 3 below, shows the power consumption per round trip and the suggested charging time in order to provide enough energy for the completion of the three round trips between Salthomen and Vrångö. The table shows that after the third round, the total amount of energy left is 30 kWh but, the vessel stops one hour before proceeding with the shorter route 283. During this stoppage time, the vessel has the opportunity to charge at least 300 kWh, sufficient for incoming trips. Hence the need for a 300 kW charger is needed for this Saltholmen charging station.

Table 4: Power consumption and suggested charging time

Stored energy in the battery [kWh]	Salthomen		Approx. stop time	Suggested stop time	Charged energy	Vrångo		Approx. stop time	Suggested stop time	Charged energy	Energy consumed/ round trip [kWh]
369	start 1st round trip	1st stop	5'	10'	+50		5th stop	5'	10'	+50	-310
		2nd stop	1'	1'			4th stop	1'	1'		
		3rd stop	3'	10'	+50		3rd stop	3'	10'	+50	
		4th stop	1'	1'			2nd stop	1'	1'		
		5th stop	1'	1'			1st stop	1'	1'		
259	start 2nd round trip	1st stop	5'	10'	+50		5th stop	5'	10'	+50	-310
		2nd stop	1'	1'			4th stop	1'	1'		
		3rd stop	3'	10'	+50		3rd stop	3'	10'	+50	
		4th stop	1'	1'			2nd stop	1'	1'		
		5th stop	1'	1'			1st stop	1'	1'		
149	start 3rd round trip	1st stop	5'	10'	+50		5th stop	5'	10'	+50	-310
		2nd stop	1'	1'			4th stop	1'	1'		
		3rd stop	3'	10'	+50		3rd stop	3'	10'	+50	
		4th stop	1'	1'			2nd stop	1'	1'		
		5th stop	1'	1'			1st stop	1'	1'		
30	The vessel stops for 1 hour then start the new shorter route 283										

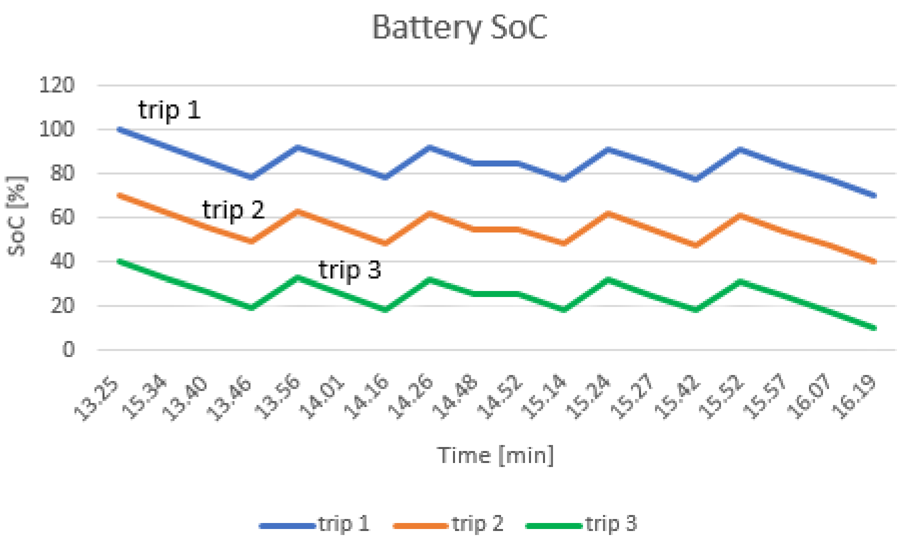

Figure 13: SoC graph

4.3 Document Analysis

The intenal research made in Volvo Penta is a case study of the “Älvsnabben 4” ferry, operating on the Göta River with end stations at Klippan and Lilla Bomen and four intermediate stations.

The ferry capacity is a maximum of 448 passengers and is equipped with two Volvo Penta D12 MH engines, each giving 450 hp, and a cruise speed of 12.5 Knots.

To determine the electrical driveline specifications, energy storage sizes, and charging demands, measurements of the propeller-shaft power consumption were performed during a full round trip.

Based on the measurements it was determined that the total energy consumption is around 73 kWh. The total resulting energy consumption, after considering the parasitic and hotel loads, is between 162 and 210 kWh.

The report concludes that each round trip requires 22 minutes of charging with 2x300 kW or 14 minutes with 2x450 kW charging power and, the total increase in time for the round trip is 15 minutes. Based on the study it is not possible to equip the ferry with a battery that can allow daily operations without intermediate charging.

5. Discussion

In this chapter SWOT analysis is used to analyze the outcome of the literature review as well as the results from the case study. The main aim is to identify the strengths, weaknesses, opportunities, and threats of the project.

5.1 SWOT Analysis

Strengths of Research

The most obvious strength of electrifying any kind of vehicle including the marina types, especially from an environmental point of view is to reduce greenhouse gas emissions. The electric driveline, besides being more efficient than the traditional ICE, involves fewer components thus leading to less maintenance, and operational costs and reducing leaks caused by conductor exposure. Ferries such as Vesta operate in urban cities/areas which are crowded and noisy, hence the need to reduce noise pollution.

Furthermore, WPT provides good electrical isolation, assuring safety, dependability, and is suitable for humid and saline environments. IPT provides galvanic isolation and safety, it also has the capability of supporting high power levels. Therefore, suitable for charging larger ferries. It offers alternative charging systems such as fixed, mobile, and multi-degree-of-freedom depending on vessel requirements. The functioning principle of CPT avoids the need for physical contact, and it is a suitable solution for submersible solutions, minimizing the needed area. It has a low EMI and high-frequency operation.

Weaknesses

The battery is an essential component in an electric vehicle, but the production, manufacturing, and dismantling have a huge negative impact on the environment: the GHG of current lithium-ion batteries (LIB) are around 150 – 200 kg CO_2/kWh [47]. Another aspect to be considered is the high initial cost of implementing the charging infrastructure. To provide the same range as a traditional ICE driveline, more batteries are needed to be installed on the ferry leading to more weight. It should be noted that a detailed analysis of the battery technology, the ferry's characteristics, and the propulsion system are factors to consider when calculating the exact weight increase in percentage. To keep lower weight, there is a need to increase the charging stations and frequency of the ferry leading to a further increase in the cost of infrastructure. Longer charging time when compared to the traditional refueling process. Increase in energy demand due to general trends in electrification in all transport sectors which will have implications on the grid supply capacity.

As a weakness of WPT, the complexity of auxiliary DC/DC converters and additional resonant components increases costs. It also requires further efficiency improvement for high-power applications. IPT has limited efficiency compared to conductive technologies and inrush currents can occur as well as synchronization issues in AC-based propulsion systems. Galvanic isolation might necessitate the use of an on-board transformer leading to consequences for cost and efficiency. CPT has limited power range, efficiency, and distance capabilities when compared with other wireless charging solutions. There is also limited availability of ferries-specific research and commercial applications.

Opportunities

High pressure on the grid supply leads to the implementation of smart grid opportunities and the integration of renewable sources of energy. Electrification will lead to a constant need for improvements and growth of charging infrastructure, thus the opportunities for business related to infrastructure and recycling or second use of the battery. Thus, the infrastructural opportunity for wireless charging can be built upon the existing charging infrastructure and re-usage of old batteries.

WPT offers the opportunity to integrate with smart grid technology for more efficient power management. Smart grid capabilities such as load management, demand response, energy balancing, and grid resilience should be leveraged to enhance the reliability, sustainability of power systems, and the overall efficiency of WPT. Through better coil design and control algorithms, there is an opportunity to improve the power conversion efficiency of an IPT system. This is achieved by optimizing the shape, size, and placement of the coils and by regulating control algorithm parameters such as current, frequency, and voltage. CPT can contribute to research and development of power range and enhance underwater power transmission with future development for marine applications.

Threats

An increase in battery demand results in direct consequences in raw materials demand. Higher request for raw materials leads to more mining and depletion of natural resources. Batteries also pose concerns on safety issues that still need to be fully addressed. The recycling of batteries is a process under development that needs more research. Just as traditional fuel, electricity can also be subjected to price fluctuations.

A major problem of WPT can be represented by the competition from other charging technologies that are more efficient and less expensive. Regulatory issues and EMI could also represent a future threat. CPT has limited commercial options designed specifically for the ferry sector. Safety concerns can also be an issue in the IPT.

Table 5:SWOT analysis summary

STRENGHT	WEAKNESSES
• Reduced emissions and noise • Efficient and simpler driveline • Less maintenance interventions • Operational cost reductions • Eliminates physical contact. • Suitable for humid and saline environments • Provides galvanic isolation, safety, and dependability. • Eliminates corrosion problems occurring in CCS. • Operating high-power levels	• GHG emissions in the LIB production • High cost of implementation • Frequent and longer charging stations/time. • Grid supply capacity • Complexity of components • Efficiency limits, power range and lack of research tailored for ferries. • Inrush current and additional components for galvanic isolation •
OPPORTUNITIES	**THREATS**
• Smart grid technology integration • Improvement in infrastructure • Infrastructure and recycling Business opportunities • Improvement in power conversion and efficiency • Underwater power transmission for marine applications	• Raw materials demand • Safety and recycling issues • Price fluctuations • EMI and regulatory issues

5.2 Adopted Solution

Based on the literature reviews and the swot analysis made in previous chapter 5.1, the following wireless power system structure is recommended. The system is divided into the following parts:

- Substation
- Floating dock/onshore system
- Coil pads
- On-board system

The schematic shown in figure 14 visualizes the system topology.

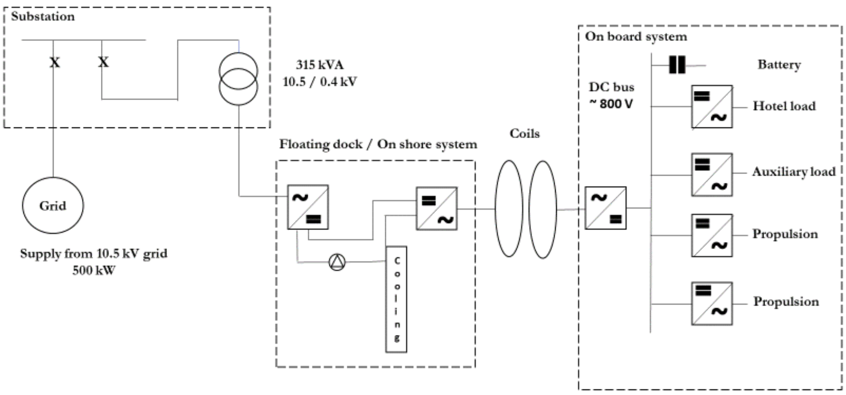

Figure 14: System topology

5.2.1 Substation

It was decided to adopt a substation with a grid supply of 10.5 kV, 500 kW that is connected to switchgear and a stepdown transformer. This was chosen because the supply from the existing grid solution aligns with the needed power supply for this research. The step-down transformer is used to step down the voltage from 10.5 kV to 0.4 kV. The circuit breaker, metering, and protection equipment are installed in the switchgear. These components are physically organized in a compact structure called a substation.
The transformer suitable for MV was chosen based on [48], having the following specifications listed in Table 6 below.

Table 6: Transformer specifications

Parameters	Values
Power kVA	315
Primary voltage kV	10.5
Secondary voltage kV	0.4
Vector group	Dyn11
Cu losses W	3300

5.2.2 Floating Dock / On-shore Power System

The shore already has an existing floating dock used for passengers to get on and off the ship safely. The floating dock will house a part of the fast wireless charging system which consists of the inverter and the rectifier. The purpose of installing this on the floating dock is to prevent too many vertical errors between the ship and the dock which are caused by the changes in water levels during the year.

Another system that can help compensate the vertical error caused by water and tidal movement is the Wartsila tide compensation device [49]. The system is shown in Figure 15 below.

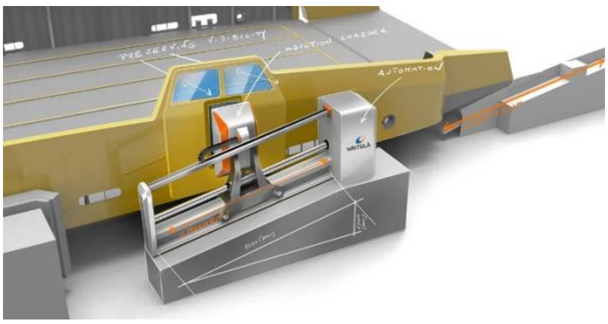

Figure 15: Tide compensation device [49]

Inverter

Wireless power transfer over coils will require the voltage to be AC. Using a full bridge inverter to convert the DC power to AC power which means that the peak voltage will be the same as the DC supply voltage. While using half-bridge inverter results in a half-DC supply, which requires transforming the voltage into a higher one. Insulated gate bipolar transistor (IGBT) was preferred due to its high-power applications, but MOSFET can also be considered. The inverter consists of four IGBTs and four diodes with each IGBT having its own gate signals serving as determinants for open or closed electronic switch position. IGBTs open and close in diagonal pairs: A pair is opened while B pair is closed, and vice versa. DC source will be inverted into an AC signal by using a specified frequency. A recommended high power switching frequency of 4-8 kHz was used in this project [50].

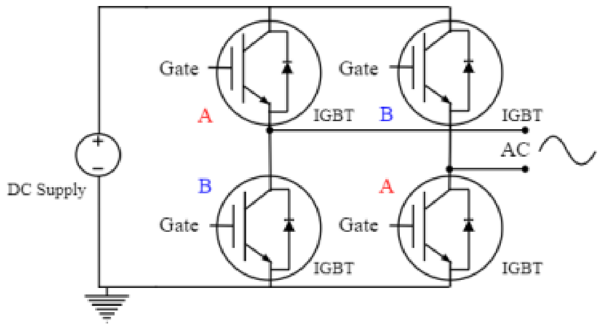

Figure 16: Inverter [51]

Rectifier

As mentioned in [52], to feed the DC load from the grid, AC/DC power electronics circuits between the grid and the DC bus are required. For an incoming three-phase AC supply, a three-phase rectifier should be used. The bridge rectifier is followed by a large filter capacitor at the input stage of the AC/DC power converters.

With the passive AC rectification, the input current drawn from the grid is not sinusoidal which results in deteriorated current waveforms. The distribution transformers are affected by the same harmonic current resulting in an expensive electricity network.

Based on the study done by [52], a three-phase six-switch PFC boost rectifier is the topology to get the constant DC voltage with fewer harmonics. The study also shows that the efficiency of the power factor has the most favorable values for this topology.

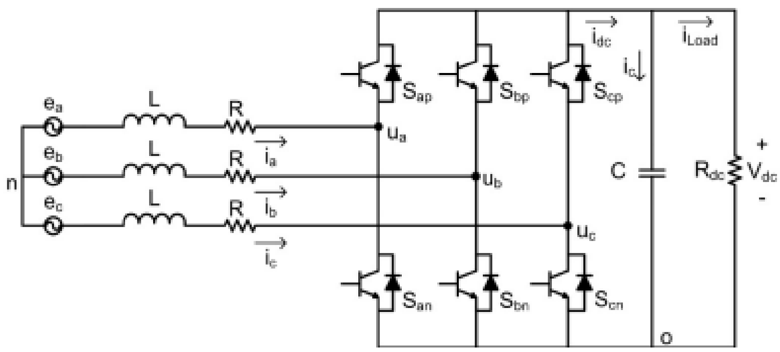

Figure 17: Three-phase six switch rectifier [52]

Compensation topologies

There are four main types of compensation technologies which are:

- SS: Series-series
- SP: Series-parallel
- PS: Parallel-series
- PP: Parallel-parallel

The gap between the transmitting and receiving coil leads to a leakage inductance that reduces the magnetization flux and mutual inductance. The compensation takes care of the leakage and improves the power transmission which is achieved by adding capacitors on both sides.

The main function of the compensation capacitor on the primary side is to reduce the reactive power. For the secondary side, it minimizes the inductance of the secondary coil and maximizes the power transfer capability.

For the suggested wireless system, a SS compensation was selected as it is preferred for high power transfers and requires fewer components which makes it an easy and reasonable solution.

SS selecting compensation capacitances depend only on the self-inductances and are independent of the load and the magnetic coupling.

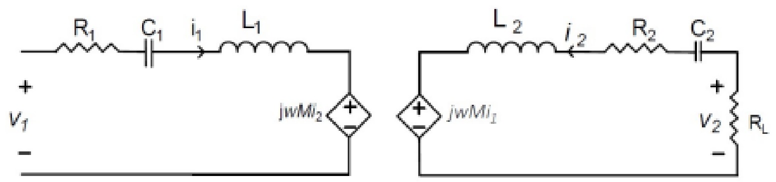

Figure 18: SS compensation [52]

Coil pads

The coil design is based on the transmitting and the receiving coil which are essential parts of the IPT. The position of the transmitting coil is usually installed on the shore or on the floating deck, while the receiving coil is always on the ship side. When docked at the shore, the positioning of the service ship(s) will have variations in all directions but mostly in the vertical direction. Position misalignment during charging due to the upwards and downwards movement of waves is expected and side, and airgap increases and decreases from sideways movement should also be expected.

Although the design of the coil is out of this project's scope, a brief highlight was made based on the previous study [7]. An H-bridge module with a 690 V voltage source converter (VSC) and IGBT transistors with 500 kW/m^2 power and an area of 0.29 m^2 can transfer about 100 - 150 kW. A rectangular-shaped coil is well suited due to its better alignment capacity [53].

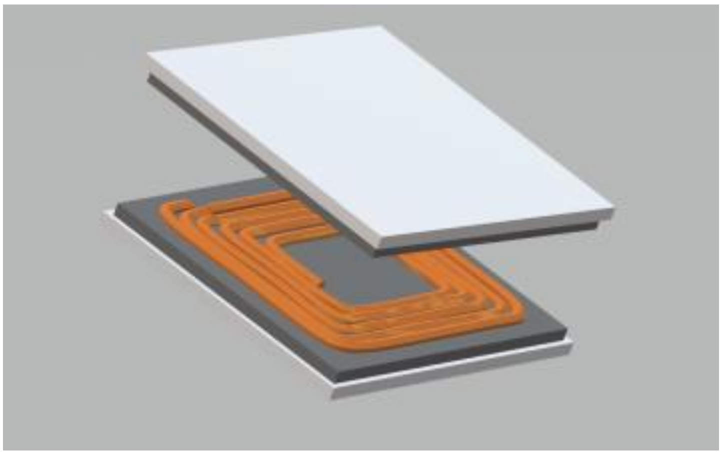

Figure 19: Coil layout [7]

On-board system

The receiving coil is placed on the side of the ship alongside an on-board rectifier which then converts the voltage from AC to DC, but the voltage does not match the DC-Bus or the battery for the vessel of 600-800 V because the voltage is still in the same region after the conversion. Hence the need for DC/DC converter to be connected after the rectifier, typically a bulk converter.

As IPT technology in marine applications is the main purpose of this project, the control strategies were not investigated due to being out of scope. DC/DC converter after voltage supply and pulse density modulation, are the control strategies that could be used to regulate voltage supply.

Cost analysis

An analysis presented by [54] at the international council of clean transportation (ICCT) shows that the implementation of the conductive charging infrastructure can vary from 45,000 $ for one charger/site for 50 kW to 65,984 $ for one charger/site for 350 kW. The total cost decreases based on the number of chargers per site. The study concludes that the infrastructure costs are relatively modest, and the trend is steadily decreasing on a per-electric-vehicle basis.

Due to lack of data in the marine sector, it is still difficult to have precise estimated values. It is important to note that these are estimated costs.

The following values are acquired based on current market value from the industry experts and original equipment manufacturers (OEM):

- Coil pads: 50,000 $ to 100,000 $
- Power Electronics: 80,000 $ to 150,000 $
- Additional equipment (transformer, filters, other system requirements): 10,000 $ to 50,000 $
- Communications and control systems (sensors, communication modules, software): 20,000 $ to 50,000 $.

Therefore, a roughly estimated value for the WPT charging infrastructure is between 162,000 $ to 350,000 $. Unfortunately, the estimated values could not be compared with existing suppliers due to no access to their price data.

6. Conclusion and Future Work

This chapter shows the reflections and answers to the research questions, and the goals and highlights the possibilities of future research.

6.1 Conclusion

Based on SLR and the deductions from the case study, it was determined that to transform route 281 totally into an electric line(route), the ferry Vesta should be retrofitted with batteries pack of a 310 kWh capacity. The ferry should be able to charge twice during the trip between Vrångö to Saltholmen and the longer stop at Saltholmen. Furthermore, an additional 12 minutes should be added to the existing 8 minutes stoppage time, this additional time should be evenly distributed between the stop at Kärlholmen and Styrsö Skäret. As the ferry operates on two other shorter routes, it is recommended that it should be charged for a minimum of an hour before starting these other routes. This is the most favorable solution, as increasing the battery capacity to more than 310 kWh will inevitably increase the ferry's weight resulting in more energy needed to propel and disastrous consequences.

There is no existing shore wireless charging infrastructure in the Göteborg area, therefore the first implementation must be carefully studied, the solution presented in the previous chapter is theoretical and should be further researched practically before they can be actualized. Secondly, an in-depth analysis of the grid capacity along the routes should be taken into consideration. In a situation where the grid cannot supply MV power values, an additional solution should be considered such as the Skoon energy mobile battery energy storage system (BESS) [55].

The brief overview of the infrastructure cost could result in prohibitive initially but taken the evolution of the EV and charging infrastructure in the sector, gives hope that in the near future, the steady increase in electric marine vessels will lead to a decline in implementation price. Nevertheless, IPT technology has the advantage of practical viable solution for electrification, it is safe and environmentally friendly. This IPT technology is well-suited as charging solution for vessels in tight schedules and short docking time.

6.2 Future Work

Further calculations and simulations should be carried out for the practical feasibility of the implementation of wireless charging on this route.

Putting more emphasis on the development of wireless charging infrastructure could lead to the adoption of wireless charging as a standard for other marine vessel types. Furthermore, the constant increase in underwater marine vehicles.

In order to facilitate the adoption of wireless charging, adding an alternative green energy source (such as solar, wind, etc.) could come into play to help the grid in remote areas.

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