UiT The Arctic University of Norway

Faculty of Science and Technology

Wireless charging of offshore wind service vessels

Master Thesis

Henrik Fjeld Nilsen

Master’s thesis in Electrical Engineering…ELE-3900-1…May 2021

ABSTRACT

This report discusses the possibility for wireless charging solutions for electric vessels, with a focus on offshore wind turbine service. Where the charging time is minimal and safety for crew is important. Different types of wireless technologies have been studied, where the Inductive power transfer (IPT) is shown to be the preferred technology.

Inductive power transfer (IPT) grants a safe charging operation and provides high power density. Brief time between the turbines requires high power to extend the range for the vessel between the turbines. Technical design of inductive charging systems is discussed, and the general aspect of a solution developed for power transfer in the range of 4 kW to 110 kW is proposed. Various compensations were consulted from literatures on Electric boats and wireless power technology, Series-Series (SS) was adopted due to its high-power ability. The proposed wireless charging solution has been simulated and analyzed, a small-scale prototype has not been constructed due to Covid-19.

ACKNOWLEDGEMENT

First off all, I would like to express my gratitude to my supervisor Dr. Bjarte Hoff, Associate Professor of Department of Electrical Technology at The Artic University of Norway. For his kind direction and guidance of this Master thesis and through the master program. Hoff has shown his expertise and created interest around the subject.

Also, I want to show my gratitude to Doctoral Research Fellow Hussein Al-Sallami for discussing different topics with guidance and helping me with the simulation.

I will end this by showing gratitude for my parents, which has given me a proper upbringing and encouraged me to study for a higher education. And my cohabitant who has been my mental support and helped while I have studied and worked at the same time.

KEYWORDS

Battery charges, CPT, Hybrid, IPT, Marine vehicles, Wireless power transmission, Offshore wind turbine, Electric vehicles.

Table of Contents

List of Figures

Acronyms

WPT – Wireless Power Transfer

IPT – Inductive Power Transfer

IGBT - Insulated Gate Bipolar Transistor

CPT – Capacitive Power Transfer

VSC - Voltage Source Converter

MOSFET - Metal Oxide Field Effect Transistors

MCU - Microcontrollers

PWM - Pulse Width Modulation

DC – Direct Current

AC – Alternating Current

EV – Electric Vehicle

WTG – Wind Turbine Generator

SS – Series Series

MEO – Maximum Efficiency Operation

UiT – The Artic University of Norway

HVDC – High Voltage Direct Current

1 INTRODUCTION

Land mass makes up about 29% of the earth surface, but wind as we know, is also present if not even more present at seas. In recent times wind turbines have been moved out offshore due to higher wind speed, natural environment and more. With existing and planned large wind farms as the Hornsea One, Dogger bank and Beacon/Empire wind turbines still need regular maintenance and inspection like onshore. This is done by service vessels that transport people and equipment to the site. We have seen a large growth of electric vehicles, and now electric vessels is gaining momentum to reduce local pollution and costs, but are more limited in range.

Offshore wind turbines are being built in farms, meaning they have a short range between them. This gives the opportunity for electric vessels with limited range to charge at each or some turbine while doing maintenance/inspection and extend det range. Wireless charging offers better utilization of available charging time. Therefor this project aims to investigate for wireless charging solutions for electric vessels at offshore wind turbines.

Some useful preliminary literature was studied during a research project in the summer 2019. Some of this will be included in the report and referred to.

> *“If you want to find the secrets of the universe, think in terms of energy, frequency and vibration.”*
>
> *- Nikola Tesla*

2 PROJECT Description

2.1 Problem analysis

Transferring energy to recharge battery storage on service vessels requires large conductors. Wireless charging can in theory transfer the same amount of energy as conducting connection, where inductive power transfer (IPT) is most commonly researched. IPT uses the magnetic field to transfer power, if the primary and secondary coil are close and aligned properly, they provide a stable connection. Its common knowledge that the sea is moving due to waves, wind and draft constantly moving the coil alignment. Making it difficult to align the coils for the most efficient transfer.

The system must be optimized to have a high tolerance to misalignment and variations in distance. Because of physical forces the boat needs a large engine to be able to move and requires large batteries. The WPT charger must be able to deliver power in the hundred-kilowatt range.

The most dangerous part for a person is while embarking and climbing the ladder for either a larger ship or a WTG (Wind Turbine Generator). In rough sea the vessel could slam into the person, or you could simply slip in the ladder and get clinched between the vessels and structure. This is a well-known problem in the maritime industry, and the undersigned has experience from this. Pulling a large charging cable up this ladder is not considered safe.

This master thesis will investigate designs for marine application to optimize charging time and efficiency while “fast charging” at offshore turbines, and to ensure a safer charging solution for the crew. Service vessel will mainly charge while waiting for operation, but to extend the range during operation the vessel could “fast charge” at each turbine simultaneously as the crew does maintenance/inspection.

2.2 Problem limitations

There are several methods for transferring power wirelessly such as IPT, CPT, RF and Laser as examined further down. And for those reasons the report will focus on either IPT, CPT or a combined technology.

This report will be limited on the power electronics and structural design/ideas used to transfer the power. Other important factors as economy, regulations, safety etc... will need to be discussed later in, if continued with design.

The solution should not propose any large change in design of WTG, as this is a large and complex structure and preferable possibility of installation on existing WTG.

Simulation will be performed to verify charging time of the vessel and efficiency transferred. Due to the COVID-19 pandemic a small-scale prototype was not constructed.

2.3 Problem formulation/objectives

The goal of this project is to do literature study of offshore wind turbines operations, with the focus of maintenance and inspection. Investigate and propose wireless charging solutions for offshore wind service vessels, propose a complete design for charging, simulate these solutions and if time create a small-scale prototype of the preferred solution.

3 LITERATURE REVIEW

3.1 Offshore Wind Turbine Farm

Wind turbine generation has seen a massive installation progress the last years, and even more offshore. A significant advantage for offshore wind farms is a strong and more available wind, and of course the discussed topic of wildlife and nature view. A farm, meaning multiple turbines close to each other could be anything from 5 – 200 turbines.

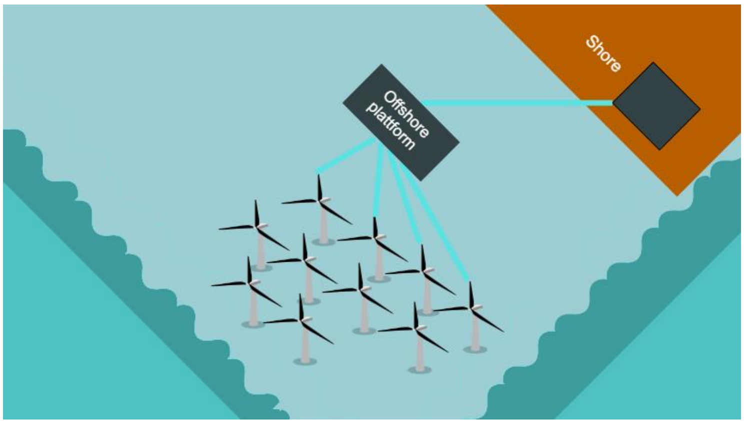


Figure 3-1 Offshore wind turbine farm

The farm is built up with several turbines connected either directly to shore or an offshore platform. The station then converts the energy to high voltage direct current (HVDC) and transfer it to shore. A commonly turbine could deliver a power between 3 – 14 MW. The turbines are placed close to each other, with no problem for electric vessels to travel between them. Traditionally three types of generators are used inside the turbine, DC, AC synchronous and AC asynchronous generators. This report will consider the generator to be 3-phase 690 V AC generator.

3.2 Service Operation at Wind Turbine Generator

When doing service operations on WTG's the vessels transport personnel and equipment out to the turbine. When boarding the turbine, the vessel continuously pushes against the structure as the overview figure below shows. The personnel can then board the structure using a fixed ladder between the two rubber cushions at the front of the vessel. This creates one contact point between the vessel and WTG, also one possible contact point is using a lifting crane from the WTG platform and down to the vessel. Also shown in the Figure 3-2. Even if it is not allowed to run the turbine while doing service operations to charge the vessel, the farm is connected to shore or an offshore substation, which it can draw power from.

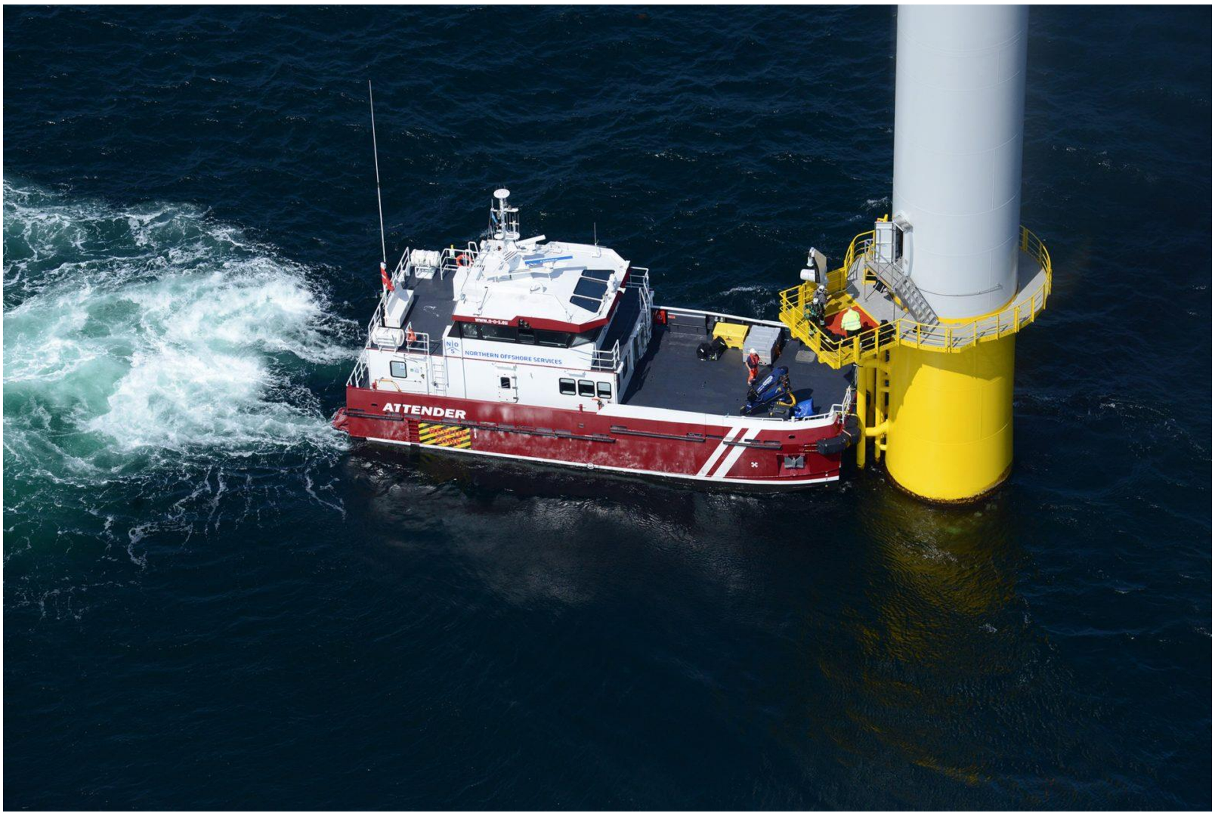


Figure 3-2 Overview Service Operation

3.3 General Transfer types

Before going more deeply in to design of the wireless power transfer of vessels, it is important that we understand the different types of power transfers that might be used. A categorization of different power transfer is shown in Figure 3-3 [1, 2]. Transfers under the acoustic field are neglected in this report.

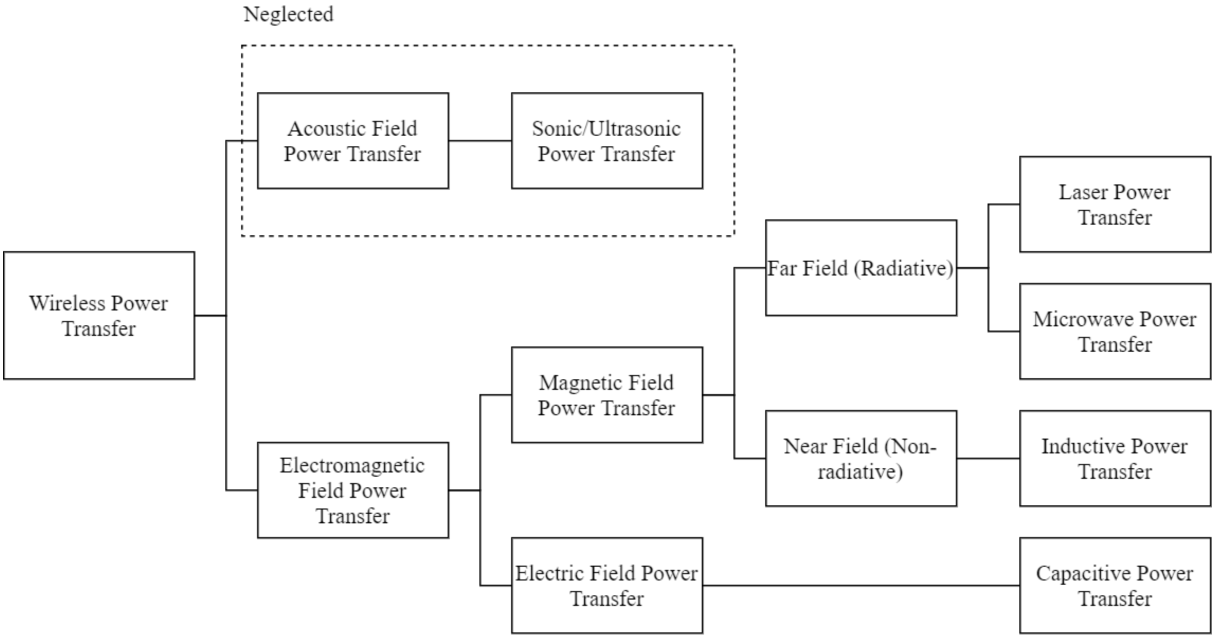


Figure 3-3 Power Transfer Topology

3.3.1 Inductive Power Transfer

IPT short for Inductive Power Transfer is a well-known concept established centuries ago by the famous Nikola Tesla. An old concept that has recently begin to make its mark in the 20th century in both small and large application. IPT is a wireless power concept that uses the magnetic resonance to transfer energy. This is done by using two identically coils as transceiver and receiver. The underlaying basic of inductive WPT is described by Ampere's Law (3.1), stating that any current carrying wire generates a magnetic field around it.

$$\oint \overline{H}\, dl = I \tag{3.1}$$

Where $\overline{H}$ is the magnetic field intensity, I is electric current and dl is the differential length current travel. By twisting the wire to a coil, it's able to concentrate the magnetic area in a much higher degree than a flat wire, this is an important factor of IPT. When a different coil enters the magnetic field of the first Faraday's law described in (3.2), states that a voltage e is induced in the second coil. Where ϕ is the magnetic flux in the coil area. Both these laws form the basics of IPT[3].

$$e = -\frac{d\phi}{dt} \tag{3.2}$$

As Dr. Soljacic has shown in his paper, it is possible to send power wirelessly over 2.1 meter. A basic principle of IPT is shown in Figure 3-4 [4, 5]. Sintef and Wartsila have already proven a system capable of above 1 MW wireless power transfer and high efficiency, for electric/hybrid ferries. [6]

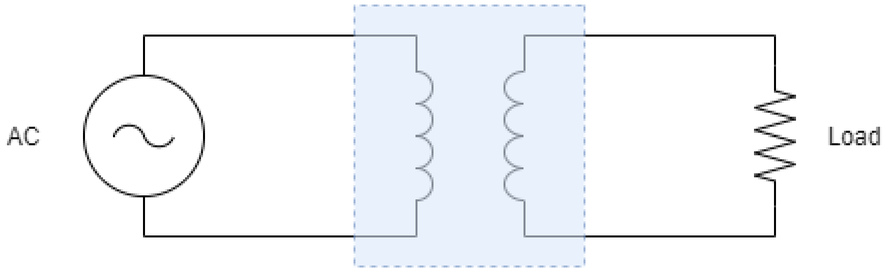


Figure 3-4 IPT Basic

3.3.2 Capacitive Power Transfer

CPT short for Capacitive Power Transfer is also a method for wireless transfer, unlike the IPT this technology uses electric field to transfer power and not the magnetic field. The technology uses high frequency alternating electric field to transfer power over a small distance. Compared the CPT is less sensitive to disturbance as the IPT, however, the range is sufficiently less.

Two plates are inserted at transmitter and receiver part, the transmitter plates are connected to each side of the supply and receiver plates is connected to each side of the load. The plates work in pairs as illustrated in Figure 3-5. When moved closed enough they act as two capacitators and creates an electric field between, allowing for current to flow. Current i and voltage v relationship is described in (3.3)

$$i(t) = C\frac{dv(t)}{dt} \tag{3.3}$$

Where C is given in (3.4)

$$C = \frac{q}{V} \tag{3.4}$$

If the charges on the plates are $\pm q$ and V is the voltage between the plates.

CPT system can maintain 2.1kW output with 90.7% efficiency at 300mm misalignment. Also, it can maintain 1.6kW output with 89.1% efficiency at 300mm distance. So, the CPT system is robust to misalignment and distance variations compared to IPT systems. A basic principle of CPT is shown in Figure 3-5. [5, 7, 8]

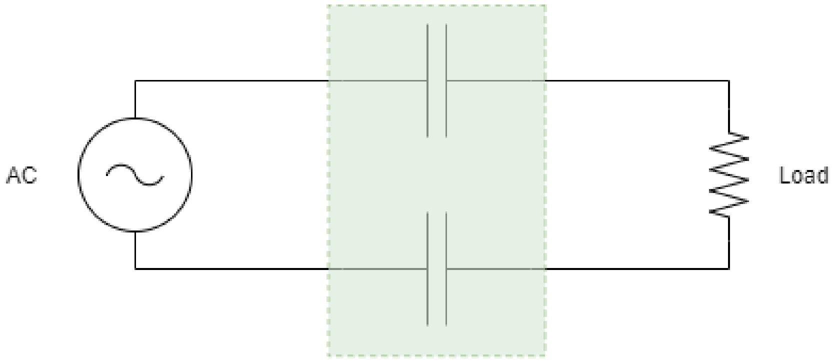


Figure 3-5 CPT Basic

3.3.3 Combined Power Transfer

Combined solutions of both IPT and CPT can improve the efficiency and make the system more robust to misalignment. Schematic of the hybrid system is shown in Figure 3-6. An important feature for application that are in constant movement. The output power of the combined system is the sum of the IPT and CPT systems, which could create a more compact WPT solutions for small applications. [5, 8]

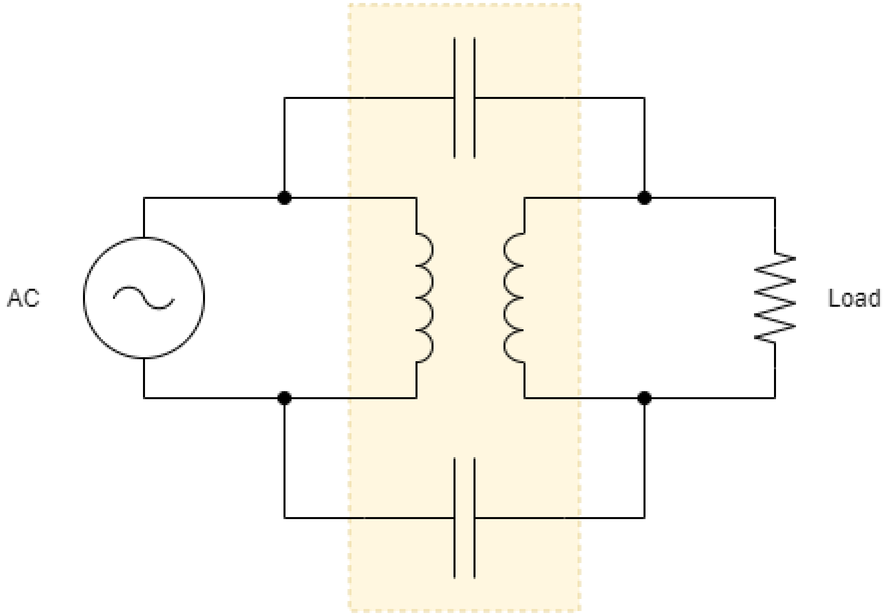


Figure 3-6 Combined IPT and CPT

3.3.4 Far Field Power Transfer

Close WPT techniques as IPT and CPT has been used for its high-power capability, but there are techniques for longer distances than a few meters. Remote strategies such as RF that we find in microwaves and lasers could extend the range much further, but certainly with less power and lower efficiency. [5, 9].

This also raises question about safety, if a person where interrupt the transmission beam of high-power RF signals or laser, results in severe damage. This seems more of an opportunity for unmanned operations.

Laser or RF WPT could therefore be used to increase range for EV's by charging them over a large distance if in sight as shown in the Figure 3-7. However, the efficiency is too low at this point to be considered as a solution for WPT, but highly interesting. Therefor long distance WPT will not be discussed further in this report.

Figure 3-7 Laser WPT

3.4 Comparison of Inductive- and Capacitive Transfer

Comparison of the WPT are given in Table 1 below, here important factors are listed. Choosing one technology depend on each project/design. Because of its high efficiency, power density and the more commonly used transfer, the IPT is chosen for this project. High power density and transfer is important factors in this project since the charging time could be minimal. The CPT still need more time to be researched to be a competitive for the IPT, but it could be a candidate because of its misalignment properties and low cost.

Table 1 PT Technology

Dis- /Advantage	***Power Transfer Technology***	
	IPT	***CPT***
Disadvanteg	*High Cost*	*Low power density*
Disadvanteg	*Eddy-current loss*	*Lower Efficiency*
Disadvanteg	*High Weight*	*Magnetic Field Emissions*
Disadvanteg	*Poor Misaligment*	*Higher safe range*
Advantage	*High power density*	*Low Cost*
Advantage	*High Efficiency*	*Low Weight*
Advantage	*Low safe range*	*Good Misalignment*

3.5 Previous Work

As mentioned in the introduction some previous study which is relative to this master thesis was done. This was a project driven by UiT which included master student to investigate different topics of charging technology for maritime and aviation. The article was written in Norwegian and the title in English is *"Different topologies in the interface between boat and land"*. Topologies discussed there is of relevance [10]. Some of the information found in this project has been a base line for this thesis. Especially the chapter about wireless power transfer using multiple coils for misalignment problems.

3.6 Efficiency

Efficiency is an important factor to discuss in wireless power transfer. There could be numerous solutions for this problem, but the preferred solutions need to have a minimum percent of efficiency. There is a small point creating technological power system with such low efficiency that the power productions need to extend ten times. Therefore, the solutions should have an acceptable efficiency. Several research papers achieve an efficiency above 90 % for WPT systems using different compensation and switching frequency. [11] [12]

In the paper [13] the researchers achieved a total power of 490 kW transfer. With an average efficiency of 90%, worth mention is that this was done using multiple coils and inverters where each transferred a part of the total power. This project will only use one system to transfer all the energy, therefore expecting some lower efficiency.

A safety system should be considered to turn off or pause the energy transfer if the system gets below 50 % efficiency. With the opportunity to overrule this feature, in case of running low on battery.

4 STRUCTURE DESIGN

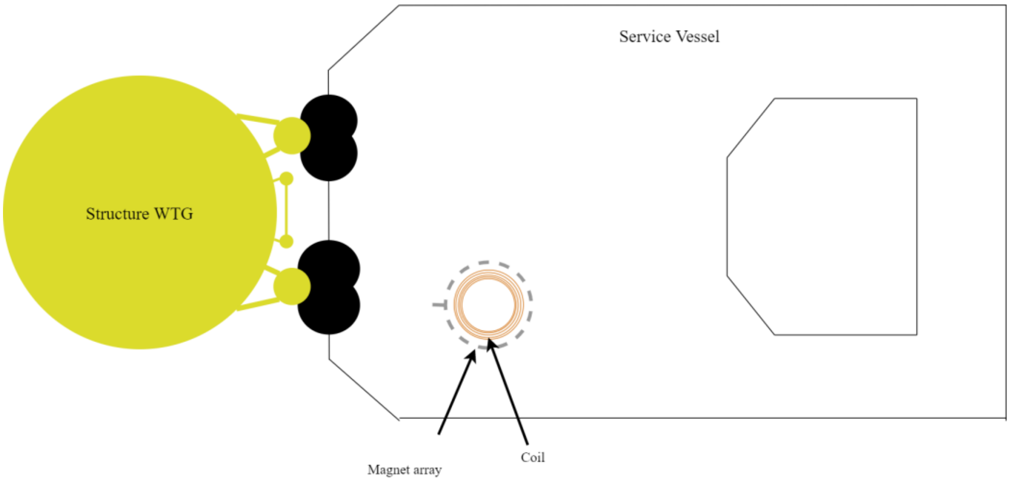
Several structure designs are given below which shows different design on power transfer between the vessels and WTG structure. The preferred design will be concluded before starting simulation and testing, because only one design will be worked on further in the report. The design should be able to install on existing WTG and the solutions should consider the below:

- Economics (inexpensive)
- Misalignment issues
- Feasibility
- Power transfer capacity
- Crew Safety
- Connection time (minimal)

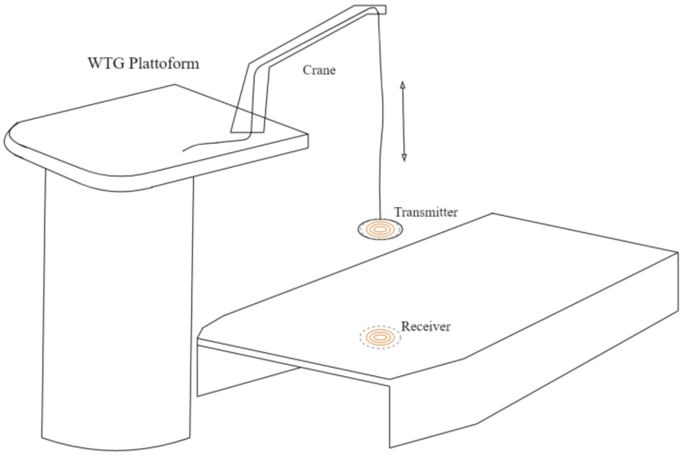
It is important that the foremost design is chosen, as this could be a standard for all vessels and offshore WTG, so that all vessels could charge on all WTG. As time is limited in this master thesis the structural design will only be ideas and not built for testing.

4.1 Quasi-Wireless

This solution uses the already installed crane on the wind turbine, which lowers the power cable with the coils on the end. The transmitter which you can see in the Figure 4-1 will connect to the vessel and stay in place by using an array of magnets. Ensuring a fixed and secure connection with a minimal distance (0-100mm) will make great efficiency and no misalignment problems. The power cable will simply hang in a slope to contract and extend with the movement of the vessel. Making the distance between the coil's constant in any weather conditions. This is an inexpensive solution with high efficiency, using an already installed crane. Connection time will be slightly higher since the crew is involved, and some WTG's does not come with a lifting crane.



A) Top View



B) Side View

Figure 4-1 Quasi-Wireless

4.2 Tracking

Illustrated in the Figure 4-2 below a robotic arm is used to constantly hold the position of the coils to maximize efficiency under movement from the ocean and wind. This design would be quite easy to install on the WTG side. The robotic arm placed on the vessel would need a control system with sensors to automatically place the coils close and maintain this position. Which makes the system more expensive and complicated. The system would start the charging process after the crew has climbed onboard the WTG. Charging time will therefor start as immediately as possible and considered as a low connection time. This will be one of the preferred solutions to test and recommend.

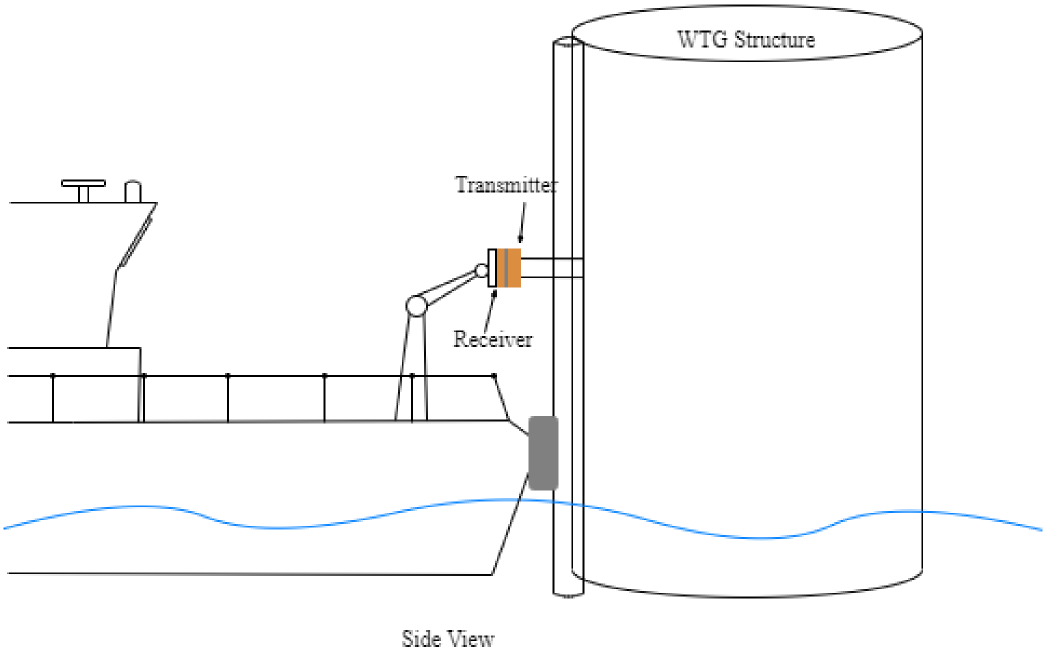


Figure 4-2 Tracking

4.3 Fixed Coils

Presented in the Figure 4-3 below shows a fixed transmitter with one or multiple coils and a fixed receiver also with either one or multiple coils. Fixed meaning the receiver is mounted on the vessel structure, following the movement of the boat, with no tracking ability. Likewise, with the transmitter on the WTG structure. The solution is considered inexpensive and simple with no or low complexity, still with a high-power transfer capacity. Possible to fit all existing and new offshore wind turbine generators. Connection time can start immediately when the vessels reach the WTG structure, preferably after the last crew personal has climbed the ladder, to ensure safety.

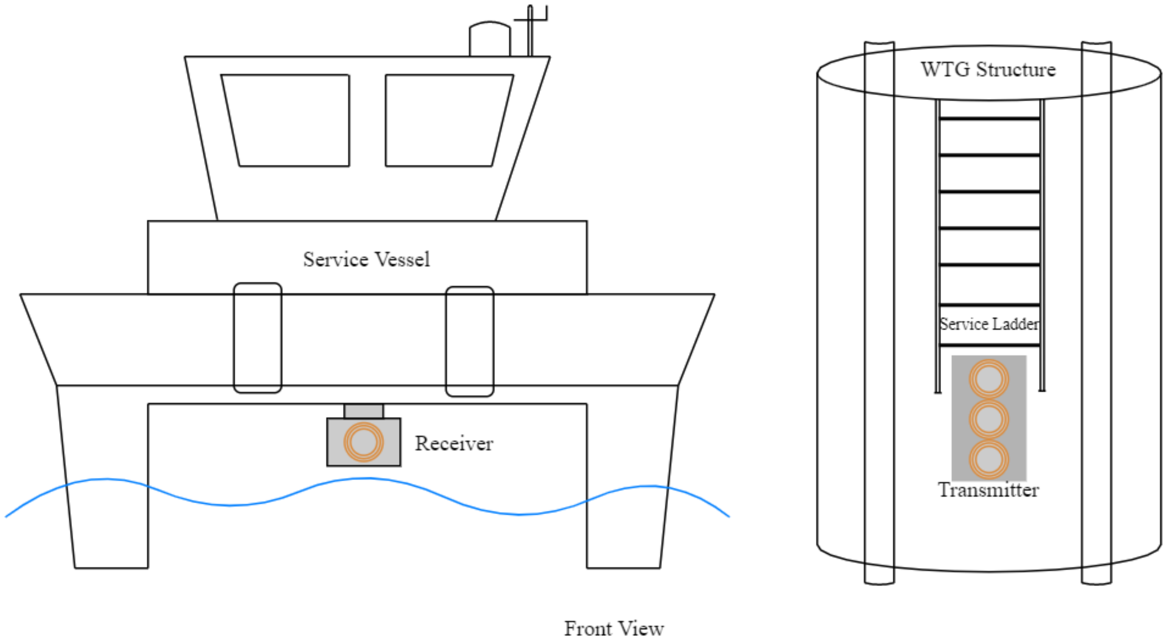


Figure 4-3 Fixed

5 Selected Topology and System Interface

The preferred structure design would be fixed coils, because of its inexpensive and simple design. Also, it would be the most uncomplex design to make a prototype for small and big scale test.

The selected topology main parts consist of:

- Power supply from either generator or grid
- Inverter to generate an AC signal
- The important compensation part on both sides, which will be SS
- Coil used for the wireless transfer
- Rectifier to convert back to DC.
- Load/Battery

Each part is shown in the Figure 5-1 below and will be described in more details in chapter 6.

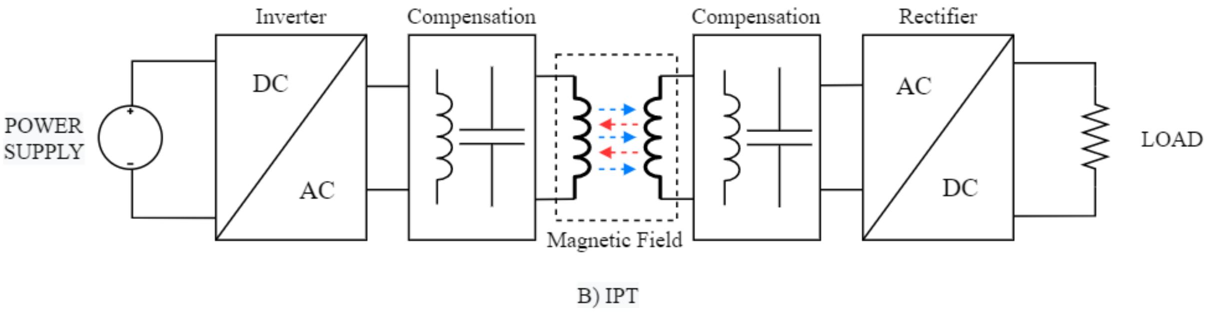


Figure 5-1 Circuit Topology

System's interface between the vessel and charging station is proposed in Figure 5-2 . The high-power charging will come from the IPT or as its commonly named *"Fast charging"*. Where it is converted to DC and matched to the DC-Bus voltage system in the range of 500 to 1000 V DC. Depending on if the vessel is using a lot of motor capacity in rough sea, the power will charge up the battery or just keep the battery level. Also, a conventional plug charged is proposed to the system so that the batteries could charge with a lower power transfer and used to service the battery lifetime while docked. It is important for modern day lithium batteries to be kept between 20-80% capacity for longer lifetime. The plug charger will be connected to the grid, where the frequency normally is 50/60 Hz. A high power transformer for this frequency has significant weight and size. Therefore, it is recommended for this charger to be around 5 kW - 22 kW which is normal for EV in households. The coils in the inductive charging will create galvanic isolation in the same way as a transformer for the plug.

This case is based on that there is a strong production of power to charge using IPT and that no energy storage at the wind turbine or onshore is needed. In a situation where there is low or no wind condition for the turbines to generate enough power. The inductive charging will imply one additional conversion stages drawing energy from the grid, connected to shore. This also depends on the grid specification (i.e., voltage level, AC/DC, and number of phases).

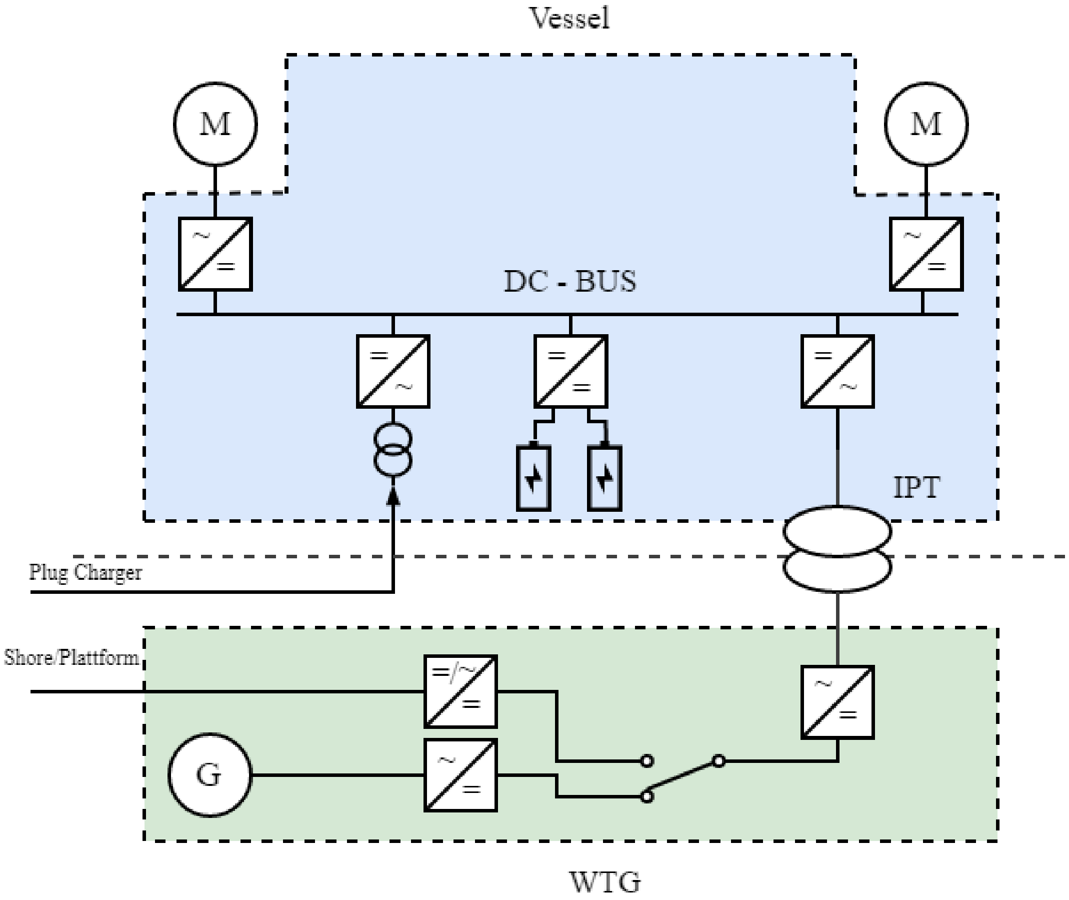


Figure 5-2 System Interface

6 WIRELESS POWER DESIGN

In the next subchapters the design of the system configuration is explained as illustrated in Figure 5-1. Formulas needed for simulation and testing are also given.

6.1 Inverter

To transmit the power wirelessly over coils the voltage needs to be AC. As presented in Figure 6-1 Inverter a full bridge inverter is used to convert the DC power to AC power. By using a full bridge inverter, the peak voltage will be the same as the DC supply voltage. If a half bridge was used the voltage would be half the DC supply, therefore the voltage would need to be transformed higher. The inverter consists of four IGBT's and four diodes. IGBT's are preferred for high power applications, but MOSFET's could also be considered. Each IGBT has its own gate signal, which determents the position of the "Electronic switch", open or closed. The IGBT's opens and closes in diagonal pairs, A pair opens while the B pair stays closed and wise versa. Doing this with a specified frequency inverts the DC source to an AC signal with the given frequency. In this project the switching frequency would be 4-8kHz which is recommended for high power[14].

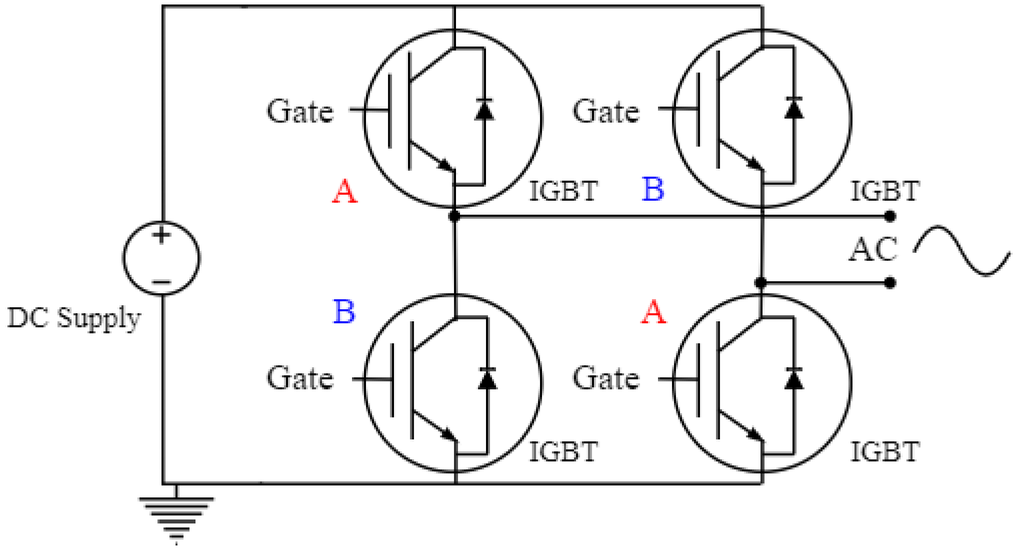


Figure 6-1 Inverter

6.2 Rectifier

The rectifier is used to convert back the AC power to DC to be connected to the DC Bus bar at the vessel side. Function as a opposite as an inverter by using diodes that work in pairs. As shown in the topology Figure 5-2 the DC power could either be used to charge the batteries or directly used by the motors. Rectifiers consist of four diodes in a full bridge connection shown below in Figure 6-2. Compared to a half bridge rectifier, this uses both cycles of the AC signal, which obviously doubles the efficiency. By pairing a capacitor with a full-wave rectifier, the current produced by the rectifier is filtered into a cleaner version of DC that is more effective and efficient.

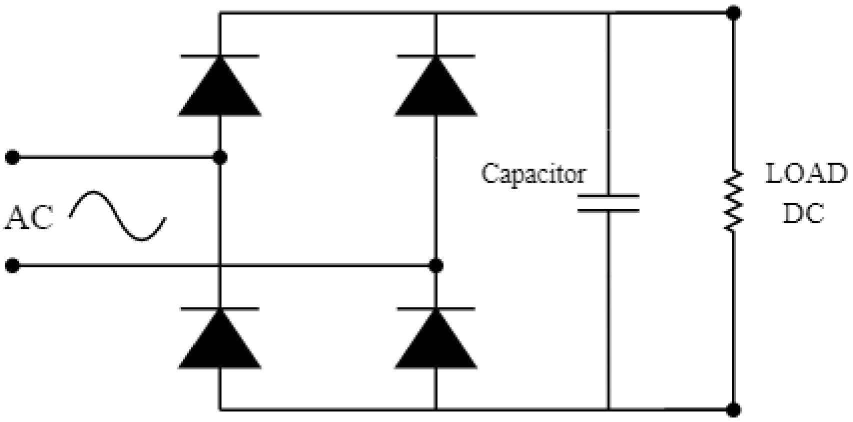


Figure 6-2 Rectifier

Choosing the correct capacitor requires calculations. Determine the value of the capacitator at the end of the rectifier is given below.

$$C = I \frac{\Delta t}{\Delta U} \tag{6.0}$$

6.3 SS - Compensation

Series – Series (SS) compensation as shown below in Figure 6-3, is usually preferred for high power transfers. Also, SS is considered an easy and reasonable solution, because of very few components. The resonant capacitors will generate high voltage across the coils, which will reduce the required current rating of coils and capacitors compared to parallel compensation. The circuit configuration for inductive power transfer has a strong filtering effect due to the resonance between the series capacitors and the inductance of the coils, and it appears as a bandpass filter for currents close to the resonance frequency [6]. Formula’s to calculate each component are given below:

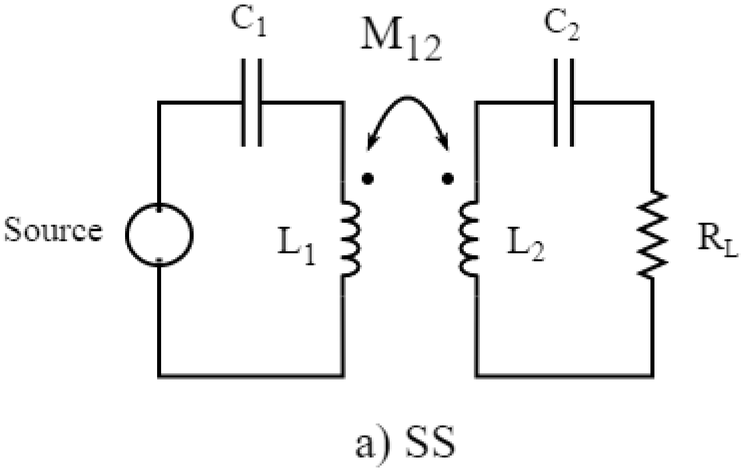


Figure 6-3 SS Compensation

Calculating M – mutual inductance with the formula

$$M = k * \sqrt{L1 \times L2} \tag{6.1}$$

Mutual inductance is proportional to the k where k is set:

$$0 \ > k \ < 1 \tag{6.2}$$

The k factor is one of the most significate factors for this system, it describes the ratio between magnetic flux ϕ at the secondary coil and the overall flux generated at the primary

[15]. Changing this coupling factor in the simulation would function as a misalignment simulation.

Calculating the SS capacitators C_n (n = 1 or 2) with the formula given from [16]:

$$C_n = \frac{1}{\omega_0^2 L_n} \tag{6.3}$$

As we can see from the formula the capacitators are dependent on the inductors L_n (n = 1 or 2) and where ω:

$$\omega = 2 \times \pi \times fo \tag{6.4}$$

Which then is dependent on fo the resonant frequency, given:

$$fo < fs \tag{6.5}$$

fs is the switching frequency, the fo should be set lower than the switching frequency, but not to far from it in order to gain voltage and current gain.

Taken from [4] the efficiency of a SS- compensated system can be calculated with given formula:

$$n = \frac{\omega^2 M^2 R_L}{[(R_2 + R_L)^2 + X_2^2]R_1 + M^2\omega^2(R_2 + R_L)}, \tag{6.6}$$

R_2 and R_1 is the resistance in the Litz copper wire coil.

6.4 Coil Design

The position of a service vessels will have variations in all directions, but mostly longitude direction when it is docked to WTG. Thus, expected changes in position during charging will be associated with up and down movement due to waves. Sideways movements that will increase or decrease the length of the airgap, must also be expected.

Based on the study done in [6] using H-bridge modules with 690 V VSC and IGBT transistors a power transferability of 500 kW/m2 was found. With a coil area of 0.29 m^2 could give around 100-150 kW transferability.

A squared shape coil is preferred because of better misalignment, shown in Figure 6-4. A full ferrite backplane could increase the coupling up to 30% [15]. The first prototype uses circular coils. Further work could test different shapes of coil layout and compare square, rectangle, and triangle. Also test the efficiency when bending the coil with the form of the vessel.

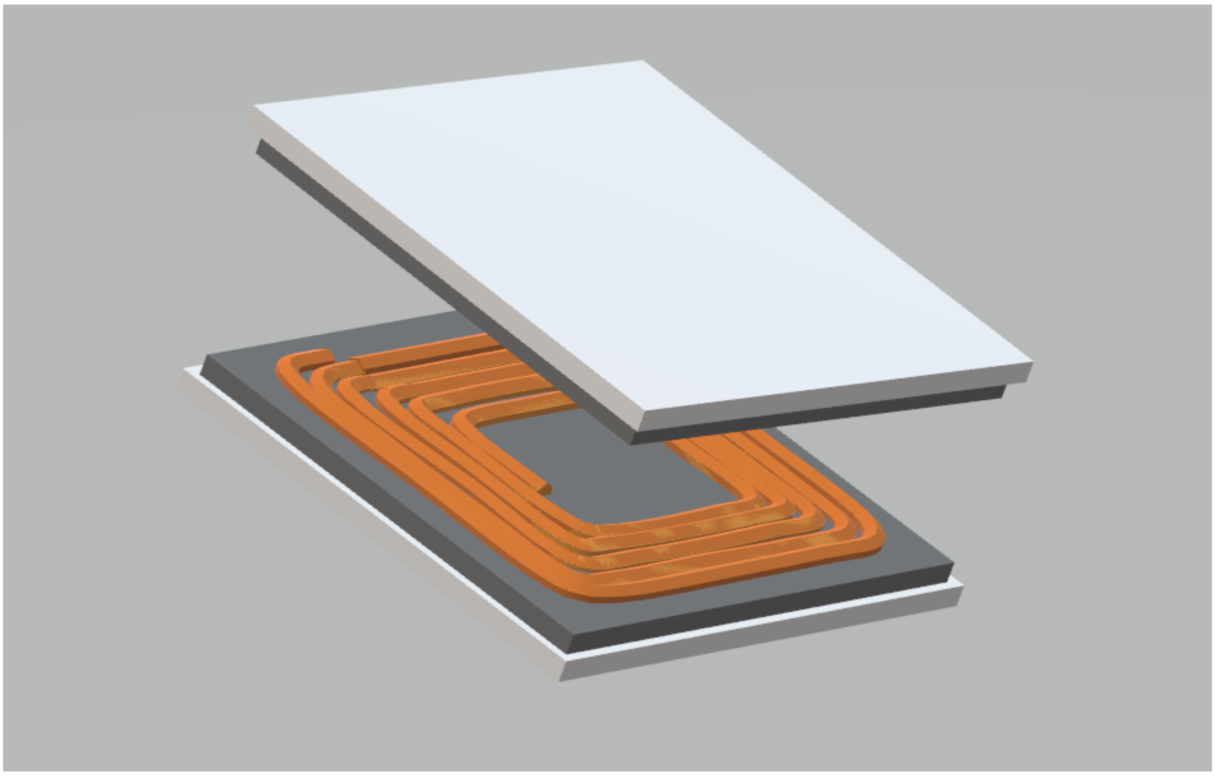


Figure 6-4 Coil layout

6.5 DC-DC Converter

When the energy has been transferred over the coils the SS compensation, as mention earlier will impose a high voltage over the coils to reduce the current. The voltage is then converted to DC after the rectifier, but the voltage is still around the same region. This will not match the DC-Bus or the battery for the vessel of 600-800V. A DC-DC Converter needs to be connected after the rectifier, typically buck converter. This is not considered for the simulation part.

6.6 Resistance Load Control

Using a fixed resistor as a load, the system will operate with a certain efficiency for this load. The system will not be able to maintain the maximum efficiency, because the efficiency is dependent on the load resistance and mutual coupling. To maintain the efficiency, the systems should implement maximum efficiency operation or MEO, for the purpose of load resistance to match the optimal load calculated. The optimal load could be calculated using the given formula for a SS compensated WPT system taken from the book [4]:

$$RL_{opt} = R2\sqrt{1+\frac{\omega^2 M_{12}^2}{R1R2}} = R2\sqrt{1+k_{12}^2 Q_1 Q_2} \tag{6.7}$$

As we can see from the formula (6.7) the optimal load is dependent on the switching frequency, mutual inductance, and resistance of the coils. As in the simulation the load resistor is a fixed Ω, but in a real system where the battery operates as the load, the load is time varying. Hence, that the efficiency will be reduced when the load or misalignment change. MEO is therefore proposed for the system to operate as close to the max efficiency as possible.

One method of MEO is standard DC-DC converter like buck-boost on the receiver side. This is already mention as an important design component to maintain a voltage that match the battery in subchapter 6.5. It can be used to match the load resistance to the optimal load, as its reported in [17]. The impedance of the converter is a function of the duty cycle for the switching inside the buck/boost converter. There are some different types of MEO, some only work when the load is less than optimal, but the DC-DC converter works for all conditions. It also has the highest cost and complexity [4]. This report will not simulate the system with MEO techniques as there is no time for, but it is proposed for the system and should be considered as future work.

6.7 System control strategies

For IPT a control system has an important role for maximizing the efficiency at different stages i.e. the end or start of the charging. The formula (6.9) describes the fundamentals of the load current [18].

$$|I_2(\omega_0)| = \frac{|U_1(\omega_0)|}{L_m \omega_0} \tag{6.9}$$

Where U_1 is the voltage supply that will be kept constant. When L_m changes due to misalignment or other factors, the current will increase and might extend the ratings. Therefore U_1 needs to be controlled, but this is a constant supply. Different control strategies could be:

- DC/DC – converter after voltage supply
- Pulse density modulation

DC/DC converters achieve high efficiency in the study [19] and is a commonly used part. The main draw back of this strategy is high hardware/software effort and expenses. Pulse density modulation could achieve the same efficiency as DC/DC converter, with lower hardware and software effort [18]. System control strategies are only mention in this report and will not be simulated; this should be considered as future work.

6.8 Two mode operation

By running two different types of power transfer operation, depending on how long the vessels will dock to the WTG. The systems can achieve a higher power transfer sacrificing with lower efficiency when charging time is minimal. For medium power transfer the system achieve higher efficiency with a decreased power transfer.

In the simulation two modes for medium and high power will be simulated with a focus on energy transferred and efficiency, compared to each other.

6.9 Power supply from WTG

The solution will consider that the power supply will come directly from the generator. This will then be AC source of ex. 690 V. When doing service operations on WTG safety rules might demand pause of power generation, meaning no power will be delivered from the generator. Therefor the power supply needs to come from the connection to shore or offshore transformer platform. This could either be AC 50 Hz or DC power, depending on the installation.

The simulation and design will consider that the power supply is DC 690 V.

6.9.1 Power output

Even if it is possible to construct a 1MW wireless power system, you do not necessary want to draw so much out of the turbine. An average offshore wind turbine generates 3.6 MW power at max [20]. A 1 MW system will use almost 1/3 of the generated power, therefor to not drain the capacity the system should be limited to 0-100 kW. Which is maximum 1/30 of the capacity of one turbine. This includes expected power production that is determined in “a day ahead” market. Power producers must supply an expected amount of energy to the market. It is also desirable that when wind turbines can produce, it should be delivered to the market immediately, as renewable energy is prioritized.

7 SIMULATION

For the simulation of the system design MATLAB R2020a and Simulink has been used as software. The Figure 7-1 below is constructed in Simulink using Simscape electrical parts. Formulas in chapter 6.3 are used to calculate each part of the system using a MATLAB script. Further in the subchapters the main parts will be discussed, which is efficiency and power output.

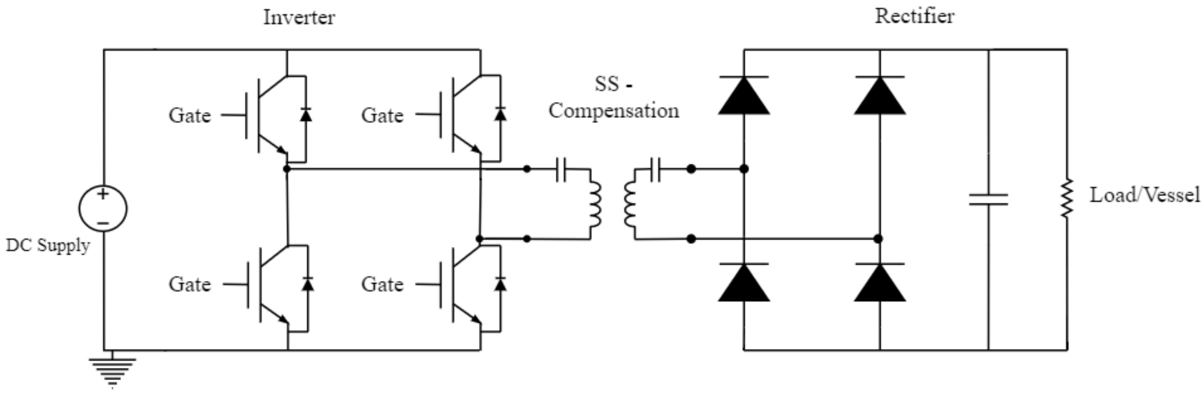


Figure 7-1 System

As mention earlier it is proposed for two mode operation which either gives high efficiency and lower output or the opposite. This is simulated in Simulink and using the same mutual inductor, hence could use the same coil for transfer.

7.1 Simulation of High Power Mode

The simulation shows that by choosing an energy transfer it effects the efficiency off the system. It is possible to achieve an output power of 110 kW with an efficiency between 74-76%. See Figure 7-2. As we can see from the figure the power is stable after steady state, also because the load is a fixed resistor.

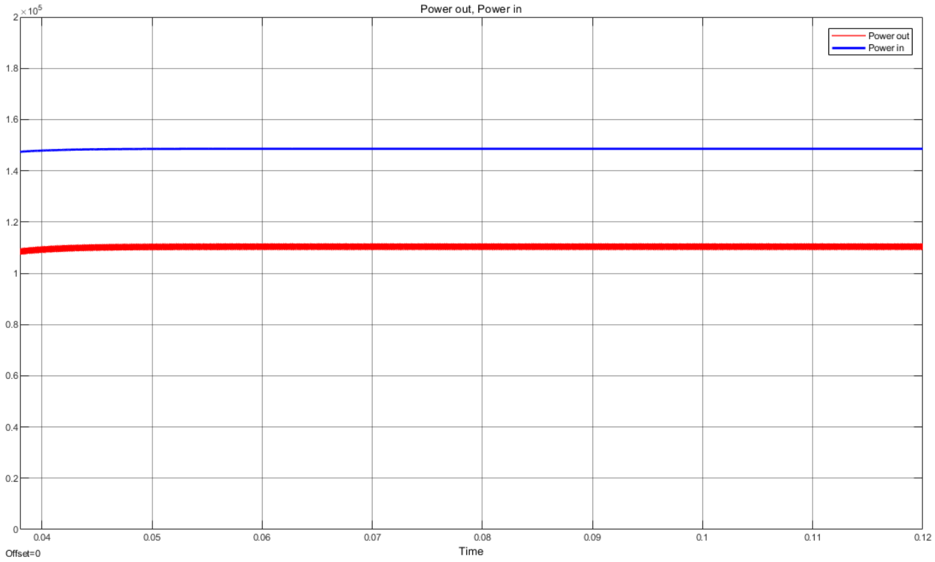


Figure 7-2 High power

Blue line shows the simulated RMS value of the current, multiplied with the voltage at the power supply. Red line is the current trough the load multiplied with the voltage across it. Hence, the power is calculated from DC domain. Based on the simulation, the system specification that required for charging using IPT technology at 110 kW is listed in Table 2.

Table 2: The suggested system specifications for high power

Parameters	***Description***	***Values***
Fs	*Switching frequency*	*4kHz*
Duty cycle	*For Pulse Generator*	*49%*
R	*Resistor load*	*100 Ω*
R_1 *and* R_2	*Resistor coil wire*	*10 mΩ*
L1	*Inductance transformer 1*	*750mh*
L2	*Inductance transformer 2*	*750mh*
k	*Coefficient of coupling* $0 < k < 1$	*0.7*

7.2 Simulation of Medium Power Mode

The simulation shows that by choosing an energy transfer it effects the efficiency off the system. It is possible to achieve an output power of 80 kW with an efficiency between 82-84%. See Figure 7-3. As we can see from the figure the power is stable after steady state, also because the load is a fixed resistor.

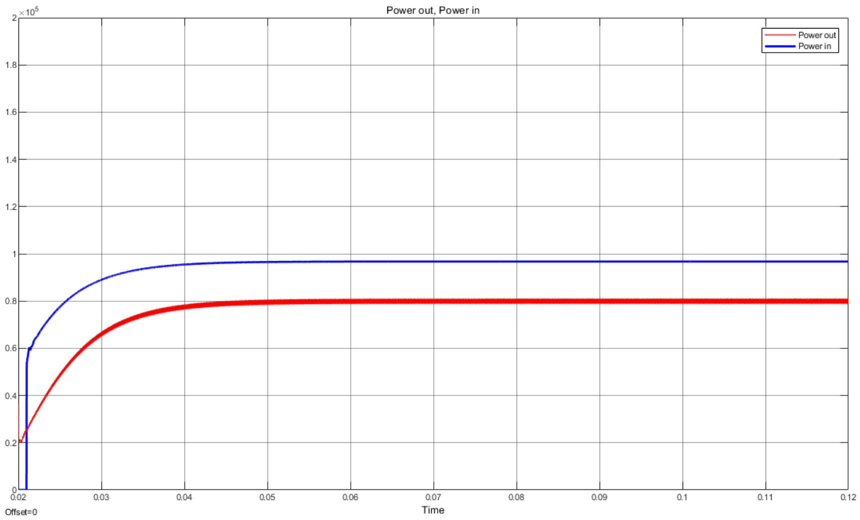


Figure 7-3 Medium power

Blue line shows the simulated RMS value of the current, multiplied with the voltage at the power supply. Red line is the current trough the load multiplied with the voltage across it. Hence, the power is calculated from DC domain. Based on the simulation, the system specification that required for charging using IPT technology at 80 kW is listed in Table 3.

Table 3: The suggested system specifications for medium power

Parameters	***Description***	***Values***
Fs	*Switching frequency*	*4 kHz*
Duty cycle	*For Pulse Generator*	*49 %*
R	*Resistor load*	*110 Ω*
R_1 and R_2	*Resistor coil wire*	*10 mΩ*
L1	*Inductance transformer 1*	*750 mh*
L2	*Inductance transformer 2*	*750 mh*
k	*Coefficient of coupling $0 < k < 1$*	*0.9*

7.3 Efficiency of the System

Calculated efficiency done by using MATLAB script using the formula 6.6 and parameters given in Table 3 for medium power mode, give an efficiency of 93%. While the simulation in Simulink only outputs an efficiency of 84%. The divergence between calculation and simulation happens because the theory does not consider switching losses and component losses, such as “on resistance” in diodes.

Presented in Figure 7-4 and Figure 7-5 are the switching signals over the IGBT’s in the inverter and current previous to coils during simulation.

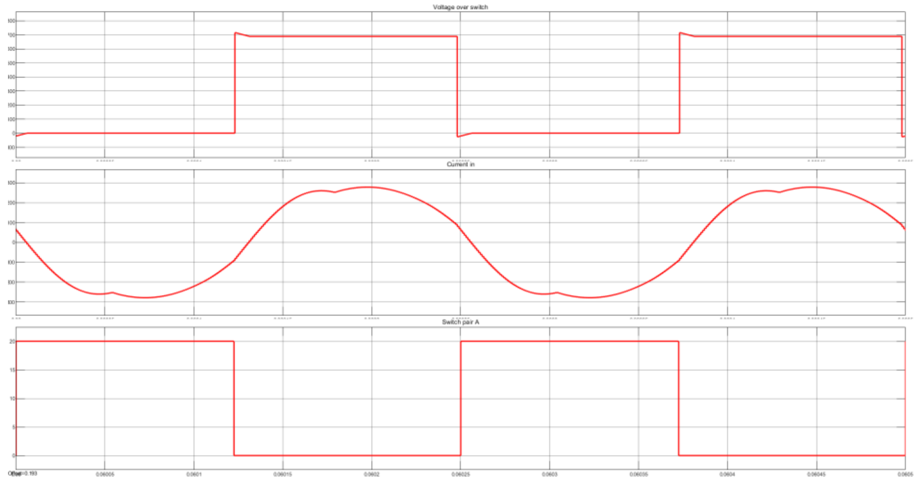


Figure 7-4 Switching High Power

From the figures we can examine an inequality when the switch turns on/off and the current wave form. When running medium power with high efficiency the current almost achieve zero before the IGBT switches, hence lower switching loss and higher efficiency. With high power mode the current does not achieve zero before the switching, thus have decreased efficiency, however it delivers increased power.

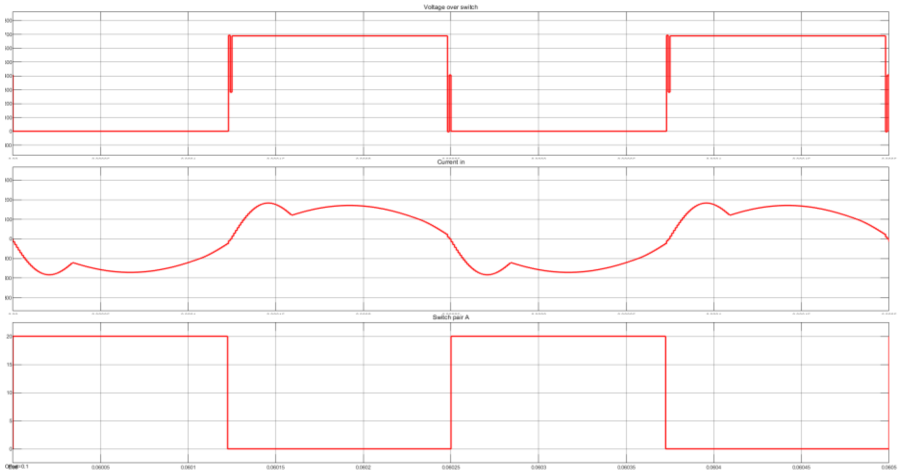


Figure 7-5 Switching Medium Power

This simulation is demonstrating a relationship among mutual inductance, and misalignment as explained in chapter 6.3 and formula 6.1. When adjusting the coupling coefficient, the efficiency decreases. Shown in Figure 7-6 are simulating with high power mode and adjusting the coefficient, blue line represent the efficiency and orange line is the output power in kW. As the figure clearly illustrates the efficiency is decreasing with the k factor, simulating misalignment. The output power peaks at a lower efficiency, but as wanted for the high power transfer. If the vessel manages to maintain a position equals to a k-factor above 0.5 the system will obtain an efficiency above 50%.

Figure 7-6 k - factor, Misalignment

In practice the systems load would be a battery, the load will constantly change dependent on the battery storage. Future work should consider the explained MEO to maintain the optimal value for efficiency.

7.4 Voltage over Coils

As deliberated in the theory for compensation the SS – compensation will induce a high voltage over the coils, which will reduce the required current rating. Presented in Figure 7-7, the top plot is the voltage generated on the transmitter side, and bottom plot is voltage on the receiver side. As the figure displays high voltage is generated over the coils while DC voltage supplied is 690 V

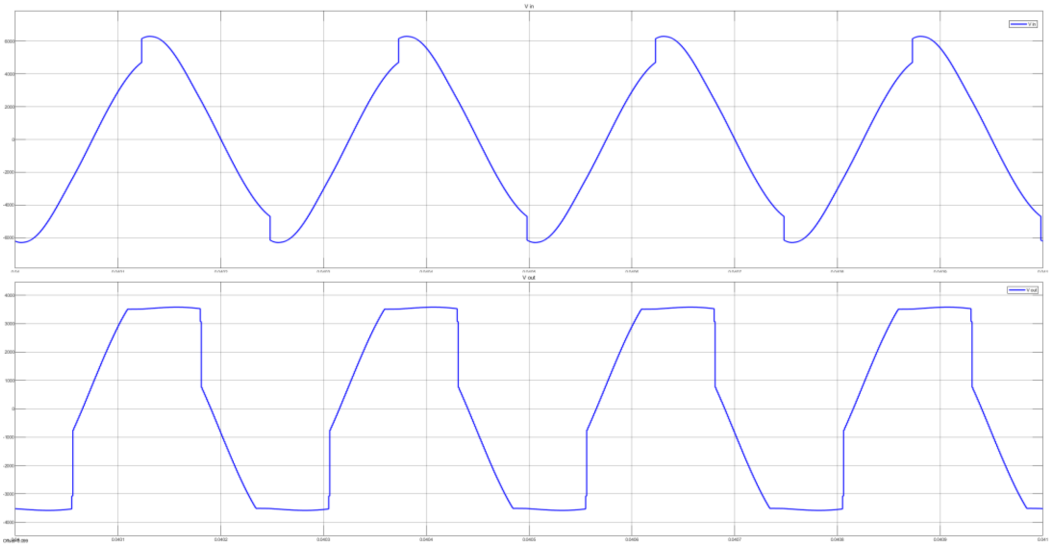


Figure 7-7 High voltage over coils

8 CONCLUSION

In this report, simulation and design of the wireless charging system is provided for electric vessel application at offshore wind turbines. By changing some parameters, the system was able to run two types of operation, one with 84% efficiency and 80 kW power transfer, and the other with 110 kW power transfer with 76% efficiency. System have the possibility to choose mode depending on the maintenance schedule and battery capacity. There is no doubt that wireless charging is possible using inductive transfer for high power application, as this report both shows and simulates to prove.

Wireless charging is a well-researched ideology, and others also prove that high power and efficiency are possible. But there will be an important question behind whether this is financially beneficial, and an HME risk for personnel. Exiting and new WTG would need an additional system (Transmitter). The suggested solution will provide an improved charging time for the vessel in tight schedules compared to wired and eliminates the wear and tear of plug and cable. By using designed system, the personnel does not need to expose themselves for dangers while connecting a cable.

9 CHALLENGES

Trouble setting the correct switch signal for IGBTS, got high short circuit currents when switching. There must be a delay between the switching pairs. Also, problems with using PWM modulator in simulation when converting the signal etc. This was an issue because of simulating from the start and not steady state, solved by skipping intuitional point.

Some struggle to create a more sinusoidal current wave for the medium power transfer, this might be solved by setting priority for voltage on certain components, but time was limited to solve/research.

Was not able to achieve higher efficiency for SS – compensation system, other compensations could yield higher efficiency and should be considered as future work.

The Corona pandemic prevented prototype testing since quarantine/isolation became an issue since hardware testing was scheduled on lab. The project was done completely digital and since the project is on a time schedule prototyping could not be done later.

9.1 Future work

- Other compensation like *LLC* or *CLLC* should be investigated as this is a more complex compensation but could yield higher efficiency. Investigate if they can deliver the same amount of power as *SS*.
- Multiple coils stacked in a vertical line to improve the misalignment during rough sea and weather.
- Different type of coils designs i.e., square, circle, triangle and shaped according to the structure of the vessel.
- Small scale prototyping on model boat, in test water pool.
- High power prototyping.
- More complex control algorithm to optimize the efficiency when the load changes
- EMI should be considered in further investigations

10 CONTACT INFORMATION

Henrik Fjeld Nilsen

Master Student UiT – The Artic University of Norway

hni056@uit.no / hefjni@hotmail.com

11 REFERENCE

[1] G. K. Ottman, H. F. Hofmann, A. C. Bhatt, and G. A. Lesieutre, "Adaptive piezoelectric energy harvesting circuit for wireless remote power supply," *IEEE Transactions on Power Electronics*, vol. 17, no. 5, pp. 669-676, 2002, doi: 10.1109/TPEL.2002.802194.

[2] S. D. Jarvis, J. Mukherjee, M. Perren, and S. J. Sweeney, "Development and characterisation of laser power converters for optical power transfer applications," *IET Optoelectronics*, https://doi.org/10.1049/iet-opt.2013.0066 vol. 8, no. 2, pp. 64-70, 2014/04/01 2014, doi: https://doi.org/10.1049/iet-opt.2013.0066.

[3] A. Triviño-Cabrera, J. M. González-González, and J. A. Aguado, *Wireless Power Transfer for Electric Vehicles: Foundations and Design Approach*, 1 ed. (Power Systems). Springer, Cham: Springer, 2020.

[4] W. Zhong, D. Xu, and R. S. Y. Hui, *Wireless Power Transfer, Between Distance and Efficiency* (CPSS Power Electronic Series). Springer, 2020.

[5] C. Mi and C. T.Rim, *Wireless Power Transfer for Electric Vehicles and Mobile Devices*. Wiley, 2017, p. 607.

[6] G. Guidi, J. A. Suul, F. Jenset, and I. Sorfonn, "Wireless Charging for Ships: High-Power Inductive Charging for Battery Electric and Plug-In Hybrid Vessels," *IEEE Electrification Magazine*, vol. 5, no. 3, pp. 22-32, 2017, doi: 10.1109/MELE.2017.2718829.

[7] C. Mi and M. A. Masrur, *Hybrid Electric Vehicles: Principles and Applications with Practical Perspectives, Second Edition*. Wiley, 2018, p. 553.

[8] F. Lu, H. Zhang, H. Hofmann, and C. C. Mi, "An Inductive and Capacitive Combined Wireless Power Transfer System With LC-Compensated Topology," *IEEE Transactions on Power Electronics*, vol. 31, no. 12, pp. 8471-8482, 2016, doi: 10.1109/TPEL.2016.2519903.

[9] Q. Zhang, W. Fang, Q. Liu, J. Wu, P. Xia, and L. Yang, "Distributed Laser Charging: A Wireless Power Transfer Approach," *IEEE Internet of Things Journal*, vol. 5, no. 5, pp. 3853-3864, 2018, doi: 10.1109/JIOT.2018.2851070.

[10] H. F. Nilsen, "Topologier i grensesnitt mellom båt og land," *Ladeteknologi*, 2019. [Online]. Available: https://site.uit.no/ladeteknologi/2019/09/11/topologier-i-grensesnitt-mellom-bat-og-land/.

[11] J. Liu, Y. Zhang, Z. Wang, and M. Cheng, "Design of a High-Efficiency Wireless Charging System for Electric Vehicle," in *2018 1st Workshop on Wide Bandgap Power Devices and Applications in Asia (WiPDA Asia)*, 16-18 May 2018 2018, pp. 40-44, doi: 10.1109/WiPDAAsia.2018.8734657.

[12] C. H. Lee, G. Jung, K. A. Hosani, B. Song, D. k. Seo, and D. Cho, "Wireless Power Transfer System for an Autonomous Electric Vehicle," in *2020 IEEE Wireless Power Transfer Conference (WPTC)*, 15-19 Nov. 2020 2020, pp. 467-470, doi: 10.1109/WPTC48563.2020.9295631.

[13] S. Shin *et al.*, "Wireless power transfer system for high power application and a method of segmentation," in *2013 IEEE Wireless Power Transfer (WPT)*, 15-16 May 2013 2013, pp. 76-78, doi: 10.1109/WPT.2013.6556886.

[14] J. Zhu, B. Liu, Q. Li, and W. Xu, "Optimization Design of Magnetic Coupling Coil for High Power IPT System," in *2020 IEEE 9th International Power Electronics and Motion Control Conference (IPEMC2020-ECCE Asia)*, 29 Nov.-2 Dec. 2020 2020, pp. 117-122, doi: 10.1109/IPEMC-ECCEAsia48364.2020.9368196.

[15] C. Joffe, S. Ditze, and A. Roßkopf, "A novel positioning tolerant inductive power transfer system," in *2013 3rd International Electric Drives Production Conference (EDPC)*, 29-30 Oct. 2013 2013, pp. 1-7, doi: 10.1109/EDPC.2013.6689747.

[16] W. Chwei-Sen, G. A. Covic, and O. H. Stielau, "Power transfer capability and bifurcation phenomena of loosely coupled inductive power transfer systems," *IEEE Transactions on Industrial Electronics*, vol. 51, no. 1, pp. 148-157, 2004, doi: 10.1109/TIE.2003.822038.

[17] Y. Moriwaki, T. Imura, and Y. Hori, "Basic study on reduction of reflected power using DC/DC converters in wireless power transfer system via magnetic resonant coupling," in *2011 IEEE 33rd International Telecommunications Energy Conference (INTELEC)*, 9-13 Oct. 2011 2011, pp. 1-5, doi: 10.1109/INTLEC.2011.6099737.

[18] J. Tritschler, B. Goeldi, S. Reichert, and G. Griepentrog, "Comparison of different control strategies for series-series compensated inductive power transmission systems," in *2015 17th European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe)*, 8-10 Sept. 2015 2015, pp. 1-8, doi: 10.1109/EPE.2015.7309309.

[19] R. Bosshard, J. W. Kolar, and B. Wunsch, "Control method for Inductive Power Transfer with high partial-load efficiency and resonance tracking," in *2014 International Power Electronics Conference (IPEC-Hiroshima 2014 - ECCE ASIA)*, 18-21 May 2014 2014, pp. 2167-2174, doi: 10.1109/IPEC.2014.6869889.

[20] W. asbl/vzw. "about-wind/wind-basics." Wind Europe. https://windeurope.org/about-wind/wind-basics/#energy (accessed.