Design, Simulation and Analysis of Wireless Power Transfer Performance for Concentric Coil using ANSYS Maxwell and MATLAB Simulink

Capstone Report

Mereke Beket

Nazarbayev University
Department of Electrical and Computer Engineering
School of Engineering and Digital Sciences

This project report was created on TexStudio editing platform using LaTeX. All the figures were drawn using draw.io online software tool.

Electrical and Computer Engineering
Nazarbayev University
http://www.nu.edu.kz

Title:
Design, Simulation and Analysis of Wireless Power Transfer Performance for Concentric Coil using ANSYS Maxwell and MATLAB Simulink

Theme:
Wireless Power Transfer

Project Period:
Spring 2025

Project Group:
Mereke Beket

Participant(s):
Mehdi Bagheri

Supervisor(s):
1

Copies: April 24, 2025

Page Numbers: 34

Date of Completion:

Abstract:

This work presents the design of an inductive power transfer (IPT) system with concentric coil geometry with simulation and analysis carried out within MATLAB and ANSYS environments. The efficiency in the simulated system was 77.63% under perfect alignment, decreasing to 75.44% and 67.74% when there was 2 cm and 4 cm misalignment, respectively. Experimental verification in air and salt water was used to show system reliability and achieved efficiencies of 71.47% and 74.57%, respectively. In misalignment tests, the efficiency decreased from 69.22% to 30.03% in air and from 62.47% to 50.55% in salt water as coil displacement was increased. Although performance decreased with complete misalignment, the system remained stable for partial displacement, indicating towards its suitability for dynamic coil position settings, i.e., underwater deployments. With a consideration for low-power operation, this work opens doors for the design of future efficient and high-power IPT systems.

Contents

Preface

The growing demand for efficient and reliable underwater energy transfer systems has become a critical area of research due to its applications in marine exploration, underwater robotics, and renewable energy harvesting. This study focuses on the design, simulation, and analysis of concentric coil-based wireless power transfer (WPT) systems for underwater environments, aiming to address the unique challenges posed by water's conductivity, electromagnetic wave attenuation, and system efficiency.

This work explores the use of concentric coil configurations as a promising solution for underwater WPT due to their capability to maintain strong coupling efficiency and minimize power losses. The study employs advanced computational tools, including Ansys Maxwell and MATLAB Simulink, to design and simulate the performance of these systems under varying operational conditions. By optimizing key parameters such as coil dimensions, material properties, and power levels, this research provides valuable insights into improving energy transfer efficiency and system reliability.

The findings presented in this article are expected to contribute to the advancement of underwater WPT technology, offering practical design guidelines and serving as a foundation for future experimental validations. It is hoped that this work will assist researchers and engineers in overcoming the technical barriers of underwater energy systems and pave the way for innovative applications in this emerging field.

Nazarbayev University, April 24, 2025

Mereke Beket
<mereke.beket@nu.edu.kz>

Chapter 1

Introduction

The paper is focused on wireless power transfer (WPT) technology, specifically aimed at underwater vehicle charging. WPT is increasingly relevant due to advances in electric vehicles, consumer electronics, unmanned underwater vehicles (UUVs), and unmanned aerial vehicles (UAVs). According to Kan et al. 2018 [1], lightweight AUVs are often utilized for tasks like coastal surveying, environmental assessment, and mine detection. They gather critical data in areas that are otherwise difficult or impossible for humans to access. Moreover, a major drawback of conductive charging is that the heavy cables used to plug in electric vehicles are hard to manage [2]. If these cables get damaged or are used incorrectly, they can cause safety hazards. Also, conductive charging systems are easier targets for theft and vandalism [2]. Wireless power transfer involves transmitting electrical energy between devices without direct electrical connections, physical contact and offers higher safety [3] . Various WPT technologies exist today categorized as radiative such as microwave and laser beams and non-radiative including inductive power transfer (IPT) and capacitive power transfer (CPT) [4]. This project concentrated on charging UUVs underwater, with a focus on IPT, which is considered optimal in terms of having higher efficiency responds to misalignment, utilizing lower frequency level and safety for this application [4]. Hughes&Gish [5] also states that one approach of wireless charging vehicles involves using acoustic signals, where a transducers change energy from electrical into mechanical and back. However, this method is less preferred because it is expensive and requires a lot of precision. Another technique is implementing beaming power system through microwaves or lasers, but in underwater environments, these waves lose energy rapidly due to scattering and spreading producing relatively low efficiency [5]. Regarding the capacitive power transfer, it was observed that the production of electric couplers entails a disproportionately large use of aluminum, raising concerns about material efficiency [6]. Inductive power transfer works by using two electromagnetically coupled coils to transfer energy from the transmitter to the receiver. When alternating current passes through the primary coil, it creates a magnetic field that induces voltage in the secondary coil, enabling power transmission between them.

The WPT field is rapidly advancing, with ongoing research and experimentation aimed at improving efficiency and range. For example, [7] researchers at the University of Michigan – Dearborn achieved 95.66 % efficiency at a distance of 20 cm with an 8 kW power output. Similarly, a team from Oak Ridge National Laboratory demonstrated wireless charging of an electric vehicle at 100 kW with a 96 % efficiency, using poly-phase electromagnetic coupling coils and rotating magnetic fields. Regarding the underwater case, the efficiency and power rate hugely depends on the coil design. Overall, the coil structure is a key part of an inductive power transfer (IPT) system because it affects important factors like efficiency, safety by controlling magnetic field leaks, compatibility with other systems, performance when misaligned, and the overall cost, size, and weight of the system [8]. For instance, [9] proposed rotation-free concentric coil design and was able to obtain 664W and 485W with approximately 92.2% efficiency depending on rotational misalignment degree. In comparison to [9] who utilized 2 transmitting coils for circular coil system, [1] employed 3 transmitters and achieved 1KW power transfer at 465KHz frequency with 92.41% efficiency at a 22mm distance. Numerous coil structures exist depending on application and system requirements such as circular ring coil, EM coupler, coaxial coil, semi-closed magnetic core, spiral and curly coil [10]. It should be mentioned that system performance does not completely depend on the coil type as same output power can be achieved with approximately same efficiency with different setup such as coil design, frequency and distance. For example, the same 1KW power transmission by [11] successfully obtained 95% efficiency at a distance of 10 mm with a curly coil structure and standard 85 KHz frequency. For transmission of 400W power [12] utilized circular ring structure and 472 KHz of switching frequency, while [13] designed a 400W power delivery system with 94.3 KHz at a distance of 2 mm based on EM coupler structure. Former received an efficiency of 86.19 %, latter obtained that of 87%.

There are several constraints for UUV underwater charging system designs which will be discussed in this paper such as commercial protocol standards. For instance, [14] mentioned that A4WP and Qi standard operate at frequencies of 6.78MHz and 250 KHz respectively, however former has a high attenuation with low efficiency while latter has power level restrictions. Not every design is allowed since there are EV standards such as SAE J2954/1, which limits implementation of desired operating frequencies [8]. Moreover, [15] indicated that in comparison to static nature of air medium, seawater is more dynamic and thus it causes some mitigation which is negatively impacts the docking process. [13] also mentions that crucial factor in analyzing and designing underwater IPT system is turbulence and high pressure. 90 % efficiency was obtained in their paper with 2 mm gap while transferring 400W and it was suggested that 4000 m depth is still feasible for

IPT underwater. Turbulence leads to misalignment issues resulting in significantly lower efficiency. Nowadays dealing with misalignment can be accomplished by four methods which are optimization of circuit structure and compensation network, control of operating frequency, coil adaptive design and optimization of multi-objectives [16]. [10] states that conductive nature of seawater creates magnetic field leakage and eddy current losses which should be carefully considered during underwater IPT system design. Additionally, relative magnetic permeability will vary in seawater due to changes in salinity level and temperature, which in turn influences mutual inductance between coils [10]. [17] also discussed divergence between water and air in terms of permittivity and permeability causing extra eddy current losses in seawater at high frequency currents and derived a theoretical equations for estimating that eddy loss. Bana et al. [18] inserted a radiation resistance to a system model to represent an Eddy current loss. However, according to [19], it is not a proper estimation and instead a multilayer solution for estimation of effects of seawater losses to mutual inductance of the system was proposed. Another method to address eddy current influence is to alter a mutual inductance model with an insertion of imaginary component and analyze it with circuit simulators as it was done by [20]. Therefore it is important to study differences in system performances in both mediums.

1.1 Importance

Investigating reliable and efficient means of powering Unmanned Underwater Vehicles (UUVs) is of vital interest due to their wide range of applications in fields of oceanographic research, environmental monitoring, underwater search and rescue operations, aquaculture, and naval security and defense. Perhaps one of the strongest pieces of evidence for the capabilities of UUVs was their instrumental participation in search and rescue activities around the Malaysia Airlines Flight MH370 disappearance. This incident emphasized the potential of UUVs in deep-sea exploration, high-definition seabed mapping, and intricate underwater search operations. Moreover, it significantly can affect to convenience of future technologies as according to Li & Mi [21], WPT allows reduction of battery capacity by up to 20%.

1.2 Methodology

The methodology is heavily based on literature review of academic articles, from journals and books written about this field. This paper will discuss the efficacy of wireless power transfer (WPT) in water compared to its efficacy in air, specifically addressing how it can reduce current issues surrounding underwater applications. The electrical conductivity of salt water, for instance, is one area where air differs from salt water, leading to the creation of unwanted eddy currents that reduce system efficiency. The study includes the overall working principles of WPT, system design, power electronics, compensation networks, and mathematical modeling, all of which will be covered in separate sections. Simulations will be carried out using ANSYS Maxwell and MATLAB Simulink, with ANSYS Maxwell being utilized particularly to analyze the magnetic characteristics of the system. There will also be an experimental setup to support the simulation output, particularly in efficiency and performance under various misalignment conditions.

1.3 Main Results

The main results were that WPT underwater can be implemented for charging UUVs without human interaction. Although, efficiency is less compared to air medium WPT, it still performs well enough at certain frequencies. Regarding the compensation network, series-series and series-parallel were preferable options from first order network, while LCC type hybrid resonance techniques were most efficient compared to other second order options. Simulation results of concentric coil design showed about 77.63 % efficiency, with subsequent decreases due to misalignment issue and reached around 67 %. At the same time, experimental setup expectedly showed lower efficiency of 69 % for air medium and 67% underwater. Moreover, misalignment had more severe impact on experimental setup reducing up to around 30% efficiency at almost fully misaligned case. Nevertheless, both simulation and experimental setup performed well.

1.4 Ethical and Professional Responsibilities

- **Ethical Responsibility:**
  The development of wireless power transfer (WPT) for concentric coils raises important ethical issues. Safety is a major concern because electromagnetic fields in IPT systems are often unsafe for humans, and may cause malfunctions in medical devices, such as pacemakers. In addressing this issue, it is proposed to reasonably consider international standards for safety (such as ICNIRP) to ensure the safety of people from harmful electromagnetic fields. The environmental implications of WPT is another significant concern when driving forces for WPT are marine ecosystems. High-frequency electromagnetic fields have been shown to influence marine life, indicating that environmental assessments must be conducted prior to WPT in ocean environments. Furthermore, access to technology is an important consideration. Wireless technologies like WPT are advanced technologies and may widen the differences between the developed and developing world, as not all countries will have the proper infrastructure to utilize them. In order to keep technology open, consideration will be given to maintaining the cost of access to technology. Additionally, the implications of military applications and the role of WPT in military applications must be taken into account when assessing WPT. For example, many of the armies of developed countries are utilizing unmanned aerial vehicles. If we are not careful about misuse of WPT, it may be used in a harmful or unethical manner. In this case, there must be ethical regulations or guidelines to ensure that WPT is used for good.

- **Informed Judgments:**
  In order to make informed decisions during this project, I will be heavily relying on technical knowledge and careful analysis. Specifically, I will conduct simulations using ANSYS Maxwell and MATLAB Simulink, which will give me relevant data in terms of system efficiency, range of operation, and safety. I will use the simulation results to inform decisions regarding the coil designs, spacing, and material selection to maximize system performance. Additionally, I will review academic papers and industry standards pertaining to wireless power transfer (WPT) technology, ensuring that my design is not only best practice but also in consideration of recently advanced technology. Honoring both theoretical research and simulations will enable me to make informed decisions that adequately recognize the scientific research component as well as practical aspects of the project. Furthermore, the researchers in Nazarbayev University have been doing research on WPT for a significant amount of time and completed simulations and a experimental lab on WPT, therefore I expect to collect the necessary guidance and assistance from either the supervisor of the original lab, or from relevant researchers in

the WPT field.

- **Global Context:**
  The application of wireless power transfer (WPT) technology internationally must take into consideration differences associated with an infrastructure capacity, regulatory aspects, and local societal demands. In many developed countries with good infrastructure and technological capacity, WPT can create significant opportunities, particularly in areas such as electric vehicles and underwater research. With wireless energy transfer, electric vehicles charging stations can operate more effectively, and unmanned underwater vehicles can recharge without direct human intervention; both have the potential to create advances in transportation and progression in marine science. However, developing nations may struggle to implement WPT for various reasons such as cost and lack of more advanced infrastructure. Even in developing countries, a lack of stable and reliable power can hinder the implementation of what has been considered an advanced technology. Developing nations may also lack the financial resources to implement WPT due to the costs associated with developing the technology. Even developed nations need to be cognizant of how environmental regulation varies worldwide. Depending on a country's environmental regulations, some nations may have more challenges with WPT based on electromagnetic interference as well as any potential impact on marine and wildlife (specifically, underwater applications). In other circumstances, a country may prioritize industry growth over environmental regulations and thus, may be willing to fast track WPT even if it may have a bigger environmental risk.

- **Economic Impact:**
  In the short run, planning and actual realization of wireless power transfer (WPT) for concentric coils may be associated with massive first capital requirements. This is mainly due to the fact that the sequential development, designing, and testing steps require expensive apparatus, competent personnel and lots of time to run the system. For them to be able to embrace this technology, they will have to use some funds to acquire the required resources. Such initial costs are usually significant, but it is necessary so as to set up a proper and responsive cost-effective structure. And yet, in the longer perspective it may turn out that WPT offers a better benefit than its costs. For instance, in industries like electric vehicles and underwater operation WPT has the potential to eliminate impairment hazards where charging or frequent servicing is needed. That would translate to reduction of operational expenses as well as saving labor. As WPT becomes common across different industries and countries, it is expected that a dramatic decline in the price of production and implementation of such systems would bulk out, hence

making the technology affordable to many industries and even regions. The problem here is that developing countries might have a hard time adapting WPT, due to its high-start up cost. To solve this, government subsidies or public-private partnerships could be considered to help make the technology more affordable. Additionally, by integrating WPT with renewable energy sources such as PV panels, companies can reduce energy costs and contribute to a more sustainable and cost-effective infrastructure in the future.

- **Environmental Impact:**
  he practice of wireless power transfer, especially when implemented with underwater systems, is known to have a significant impact on the surroundings. An urgent concern in this regard is that these systems create electromagnetic fields (EMF) which could affect the life in the ocean. Fish and other marine species that use electromagnetic signals to navigate can experience disorientation or becoming disturbed. To balance this impact during the project construction phase it is envisaged that extensive landscape studies will be conducted. On the basis of these predictions it will become easier to determine the safety of the WPT systems at any level of EMF exposure.

  Efficiency of WPT systems runs behind concern about the effect of these systems. As energy and probable efficiency of WPT systems' use is still under dispute, new energy efficient technologies have been developed to satisfy certain requirements and satisfy various objectives. That said, the project will prioritize improving the inductive power transfer system whose energy consumption is to be minimized. Besides, we will direct our efforts to the use of alternative environmentally friendly materials and the energy from the depletion of any resources. Its because, this program is part of our strategies to improve the energy processes and thus cut down the total emissions of greenhouse gases.

  By looking at these various perspectives, it is to be expected that WPT systems can be designed that are both effective and also observe environmental friendliness in that these aspects allow such systems to be easily integrated into aquatic ecosystems and allow promotion of clean energy schemes.

- **Societal Impact:**
  The purpose of this project is to achieve considerable merits to the society, which unlock new possibilities for more effective wireless power transfer (WPT) systems in underwater applications that may be useful for various kinds of projects on unmanned underwater vehicles (UUVs). The use of such products is no longer a luxury as the contemporary ocean requires them for a number of roles such as environmental surveillance, oil exploration, and scientific studies. An unmanned underwater vehicle (UUV) therefore can stay in service for long continuous time intervals and get data without stopping

for human charging. In effect, this facilitates increased comprehension of sea ecosystems.

Saying more about the advantages of WPT systems, it is clear that they would contribute to better safety by decreasing the need for human bodies in risky environments such as exploration and exploitation of the ocean depths and other similar activities. While these achievements are encouraging, on the other hand everyone has to make sure that it does not turn out to be a negativism. We also need to watch out to avoid creating more unemployment or making technology unavailable to a certain segment of the population.

To deal with these issues, public policy of the undertaken initiative would promote the principle of open source research as well as support the dissemination of WPT systems among the population. This will benefit many social strata, from troops making use of combat autonomous vehicles to scientists who carry out various research. Utilizing ethical dilemmas within the WPT technology, we can be able to have some of these advantages as a tradeoff without worsening divisions.

Chapter 2

Background

2.1 Medium comparison

One of the main differences between these two mediums is electrical conductivity of salt water. Higher permittivity and conductivity of seawater causes some extra parasitic capacitance and eddy current loss. According to Yu et al. 2022 [15], eddy current loss adds an additional equivalent resistance and equivalent capacitance to the air-to-air model. Also, he listed key problems of WPT underwater which needs to be handled in order to efficiently utilize this technology. Technical Principle of WPT in Seawater is one of key problems, thus a comprehensive and systematic circuit model needs to be obtained by considering a plethora of factors such as eddy current loss and its mechanisms. IWPT System Implementation on an AUV is another key issue, shape and hydrodynamic performance can be affected by designing an underwater IPT charging system. Communication and Data Transfer, Adaptability to the Marine Environment(salinity, pressure, depth and temperature can affect the efficiency), Electromagnetic Compatibility(it is important to take measures to reduce the electromagnetic interference) and Application of New Materials(electromagnetic metamaterials which can have significantly higher transmission efficiency are also important problems at this point of tech development. Among those factors, the marine environment should be studied more deeply in order to figure out factors resisting the efficient WPT underwater. According to [15], Efficiency decreases significantly when the pressure is 40 MPa and the water depth is 4 km. Efficiency of the WPT system decreases with increasing salinity, and the trend of efficiency decline accelerates when salinity exceeds 10%. For certain setup, the cooling effect of seawater increased the maximum power of the coil from 600 W in air to 1 kW in water.

2.2 Dealing with Eddy current

Undesirable Eddy currents occur when a magnetic field is flowing in a conductive medium of water, which takes some of the transmitting power and therefore decreases overall efficiency. To deal with this loss we can either figure out optimal operating frequency at which Eddy current is minimum or optimize coil design. According to [9], the efficiency of the system in the salt water remains stable at frequencies between 215.5 kHz and 248.4 kHz. Another option is changing coil design as it was suggested by [22]. He proposed a new coil structure given as 1x1x1 model, it is three or more parallel to each other connected coils for both transmitting and receiving sides. Experiment was conducted on a base of 2 transmitting and 1 receiving coils with shared-compensated capacitance topology. It decreased eddy current loss up to 50%, increasing overall efficiency by 10%. For the simulation in this paper, we take it as a resistance added to both primary and secondary sides of the circuit. The paper by Shafiei et al. (2025) [23] presents a comprehensive electromagnetic field model based on Maxwell's equations and cylindrical coordinate transformations to derive an analytical expression for ECLs. It was offered to separate the electric field into azimuthal components and solve the Helmholtz equation using Bessel functions, and insert additional self and mutual resistances, leading to a precise representation of field intensity in the conductive region. Moreover, eddy current power loss was proportional to the square of the electric field intensity and conductivity of the medium.

Chapter 3

Methodology

3.1 Methods for Simulation

The design, simulation, and analysis of underwater wireless power transfer (WPT) systems commonly employ two specialized software tools: MATLAB (including Simulink) and ANSYS Maxwell 3D. These software programs are widely used due to their robust capabilities in modeling electromagnetic and electrical systems. To begin with, certain constraints were imposed on the experimental setup due to practical limitations, particularly regarding the transmitting power. For safety and feasibility, the transmitting power was selected to be as low as possible, specifically within the range of 12 W to 24 W. This allowed the system to operate at a manageable voltage level of 12 V and relatively low current, ensuring both efficiency and safety during testing. Given these power constraints, an optimization process was implemented using Particle Swarm Optimization (PSO) algorithms. By providing the desired output voltage, current and specific range for other parameters as input parameters to the PSO program, an optimal coil design was achieved. The design parameters included the number of turns, inner radius, number of strands, and wire radius. This optimization ensured the coils were tailored to meet the system requirements effectively. The optimized coil parameters obtained from the PSO algorithm were then applied to construct a physical prototype of the system. Furthermore, these parameters were essential for verifying key coil characteristics such as self-inductance, mutual inductance, and resistance using ANSYS Electronics software. The mutual inductance value, in particular, plays a critical role in connecting the primary and secondary sides of the WPT system. This parameter, once calculated in ANSYS, was integrated into the MATLAB SIMULINK model to enable accurate simulation of the system's performance. Among the power electronics, high frequency inverter and rectifier were used for simulation. An inverter is used to convert the DC voltage from a battery (which can be charged using renewable sources like solar panels or wave power) into AC voltage, which is needed for an inductive power transfer (IPT) system to function. It usually includes 4 insulated-gate bipolar transistors (IGBTs) that act as switches, quickly alternating their states to produce an AC signal. High-frequency inverters, operating at 20-80 kHz, are commonly used because they improve efficiency, reduce electromagnetic interference, and allow for smaller component sizes. These inverters generate high-frequency voltage signals, which are passed through LC filters to create a smooth sine-wave AC signal while removing unwanted harmonics. There are different types of inverters, such as resonant (like LLC resonant converters) and non-resonant (e.g., quasi-resonant or active-clamp converters). A rectifier is a circuit that changes AC voltage back into DC voltage, which is typically used for charging purposes. Full-bridge rectifiers, made with 4 diodes, are widely used because they convert both phases of the AC signal into DC. On the other hand, half-wave rectifiers only use one phase of the AC signal. Their model can be seen in 3.1.

Regarding the compensation networks, they are used in WPT systems to manage reactive power, which results from energy oscillating between the source and coils without being consumed by the load. These networks, created by adding capacitors to the primary and secondary sides, help stabilize the system and reduce fluctuations. There are four main configurations based on capacitor placement: series-series (S-S), series-parallel (S-P), parallel-series (P-S), and parallel-parallel (P-P). The S-S configuration is often preferred for its stability against changes in coupling and load. However, under light loads or no receiver conditions, it can cause high secondary-side voltages, leading to unsafe operation. Advanced LCC-based compensation structures, such as LCC-S, improve system performance by offering better misalignment tolerance, lower energy losses, reduced electromagnetic radiation, and more stable output power. The S-S topology was chosen for this simulation due to its advantages such as simplicity and stability. The value of those capacitor were determined according to 3.1.

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{3.1}$$

Filter for smoothing signals after rectifier was designed using both capacitor and inductor. In order to calculate values for those components, the equations suggested by [24] were utilized. The key factor is ripple factor(RF) for the filter, and it can be assumed to be about 3%.

$$RF = \frac{1}{\sqrt{2}\,(2f_rRC - 1)} \tag{3.2}$$

$$RF = \frac{0.4714}{\sqrt{1 + \left(4\pi f_i \frac{L}{R}\right)^2}} \tag{3.3}$$

From 3.2, we can obtain value for capacitor and from 3.3 the value of inductor is received. The efficiency which will be obtained directly from simulation is mathematically calculated through 3.4

$$\eta_{\mathrm{WPT}} = \frac{k^2 Q_{\mathrm{TX}} Q_{\mathrm{RX}}}{\left(1 + \sqrt{1 + k^2 Q_{\mathrm{TX}} Q_{\mathrm{RX}}}\right)^2} \tag{3.4}$$

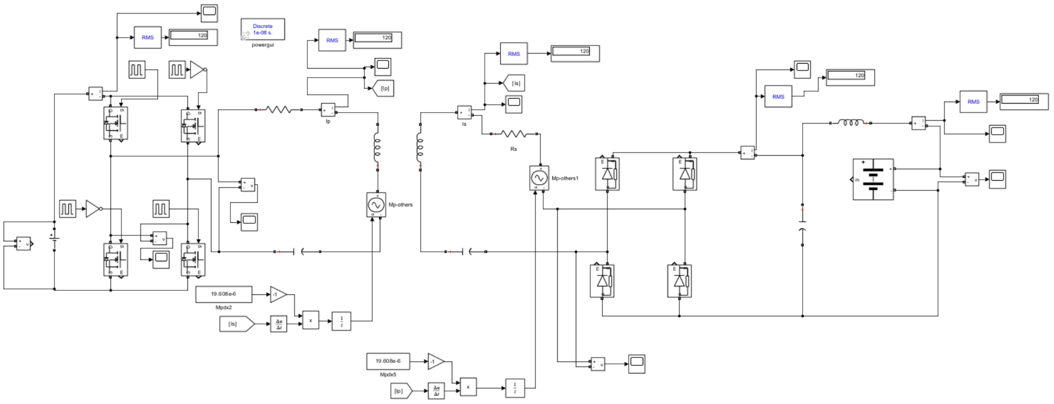


Figure 3.1: Simulink Model

3.2 Methods for Experimental Setup

To validate the simulation results, it is essential to develop a physical prototype of the wireless power transfer (WPT) system. This step ensures that the theoretical models and simulation outcomes align with real-world behavior, providing a basis for further analysis and refinement. To achieve this, various design aspects of the system were carefully evaluated, with a particular focus on the design of the inverter and rectifier. These components are critical to the system's operation as they facilitate the conversion of electrical energy between alternating current (AC) and direct current (DC) forms. Since the primary objective of this effort is to validate the simulation results and evaluate the system's performance under different conditions—such as coil misalignment—the power electronics components will be designed based on existing, well-established designs. This approach minimizes design risks while maintaining consistency with proven methodologies. Regarding the coil design, a pragmatic approach was adopted for the initial prototype. For simplicity and ease of construction, a copper wire will be used for the first iteration of the coil. Testing method will involve circuits constructed on a breadboard, where the use of copper wire with multiple strands will be first soldered together and wired with breadboard by special connectors. . To create a marine environment, sea salt will be utilized in a proper proportion of around 35% salinity level.

3.3 Optimization and misalignment

Particle Swarm Optimization (PSO) is an evolutionary computation method introduced by Kennedy and Eberhart. This technique incorporates fundamental principles of evolutionary algorithms, including the following: (1) initialization of a population with random candidate solutions, (2) iterative search for the optimal solution through successive generations, and (3) population evolution informed by the performance of prior generations[25].

In PSO, the candidate solutions, referred to as particles, traverse the problem space by adapting their trajectories based on the current best-performing particles. This dynamic adjustment is governed by two key equations, which update each particle's velocity and position during every iteration. These updates enable the algorithm to efficiently converge toward the optimal solution. According to same [25], compared to other optimization methods, Particle Swarm Optimization (PSO) offers several notable advantages:

- Simplicity: The algorithm is straightforward, requiring only a few parameters to be adjusted, making it easy to implement and use.
- Efficiency: PSO demonstrates high computational efficiency, performing significantly faster on benchmark functions. The results also indicate its capability to address a wide variety of constrained optimization problems effectively.
- Flexibility: PSO does not impose predefined limits on the objective function or constraints, eliminating the need for preprocessing these elements before optimization.

According to [26], the key parameters commonly used in the Particle Swarm Optimization (PSO) algorithm are typically set within specific ranges to ensure effective performance. The inertial weight is usually varied from 0.9 to 0.4 to balance exploration and exploitation. The acceleration factors c1 and c2 are generally set between 2 and 2.05, influencing the cognitive and social behaviors of particles. The population size, which determines the number of particles, typically ranges from 10 to 100. The maximum number of iterations is often chosen between 500 and 10,000, depending on the problem's complexity. Additionally, the initial velocity of particles is usually set to 10% of their initial position, providing a moderate starting dynamic. Application of PSO for wireless power transfer topic is properly shown in [23], where underwater IPT system was designed accordingly with results of the optimization. Regarding the misalignment tests, after successful construction of the circuit including operating high-frequency inverter, rectifier, coil design with compensation technology, the relative position of coils will be changed to simulate the nature of sea. Within the simulation, inner coil will be displaced by 1cm, 2cm and 4cm to the upward direction along Z-axis.

Chapter 4

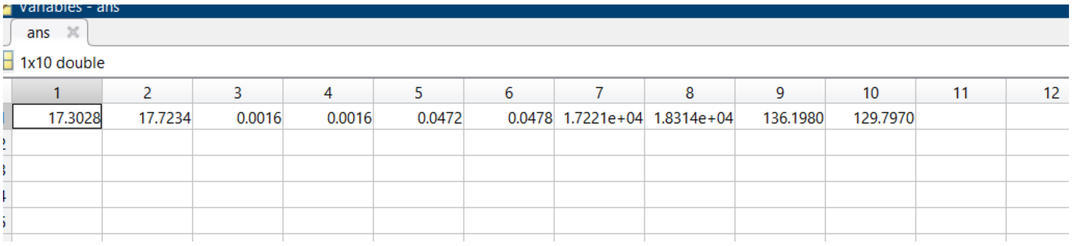
Results and Discussions

4.1 Results of Simulation

After careful research on the PSO algorithm and based on the algorithm derived and demonstrated in [27], the MATLAB code was written. Considering the design parameters for wireless transfer of about 12-24W, I was able to obtain the optimal(overall range was given to them within the program, such as minimum number of turns was 5, while maximum was 30) range for

- Number of turns: 13-14
- Screw pitch: 1.2mm-1.6mm
- Inner Radius: 4.21cm-4.78cm
- Natural Resonant Frequency: 79.672kHz-84.554kHz
- Number of Strands: 129-136

The result can be seen in 4.1 Based on that algorithm results, which utilized mathematical model of mutual inductance via complex equations, the coil geometry was built in ANSYS as it can be seen in 4.3. It demonstrated that setup initiated for transmission of small amount of power has mutual inductance of $19.608\mu H$ and self inductance of $25.69\mu H$ and $32.027\mu H$ for inner and outer coils, respectively. If we implement that Mutual Inductance into the MATLAB SIMULINK model as it can be seen in 3.1, we can obtain an operating model of the system with input source, inverting circuit, rectifying circuit, compensation capacitors and coils.



1	2	3	4	5	6	7	8	9	10	11	12
17.3028	17.7234	0.0016	0.0016	0.0472	0.0478	1.7221e+04	1.8314e+04	136.1980	129.7970		

Figure 4.1: Resulting table from PSO algorithm

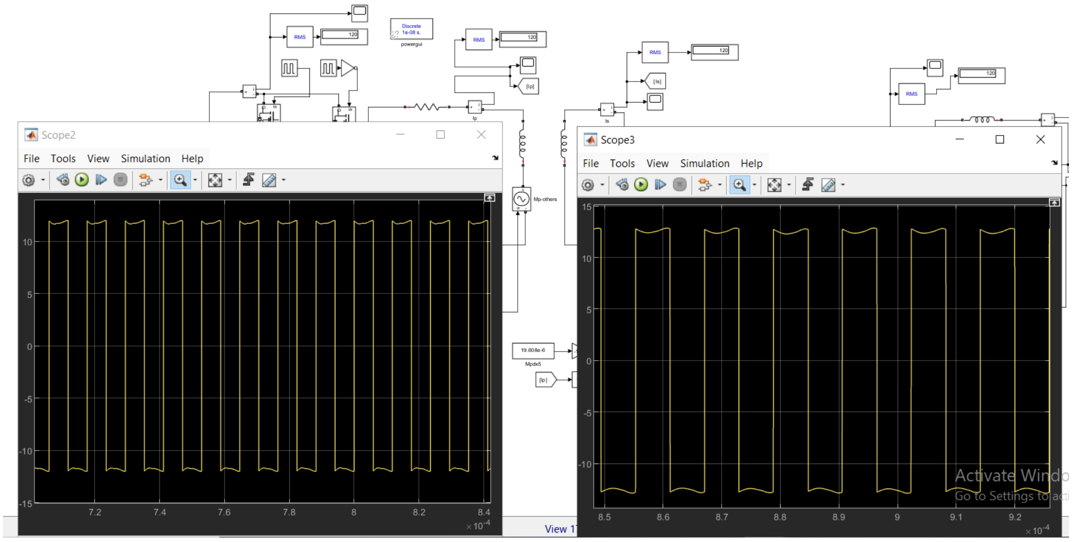
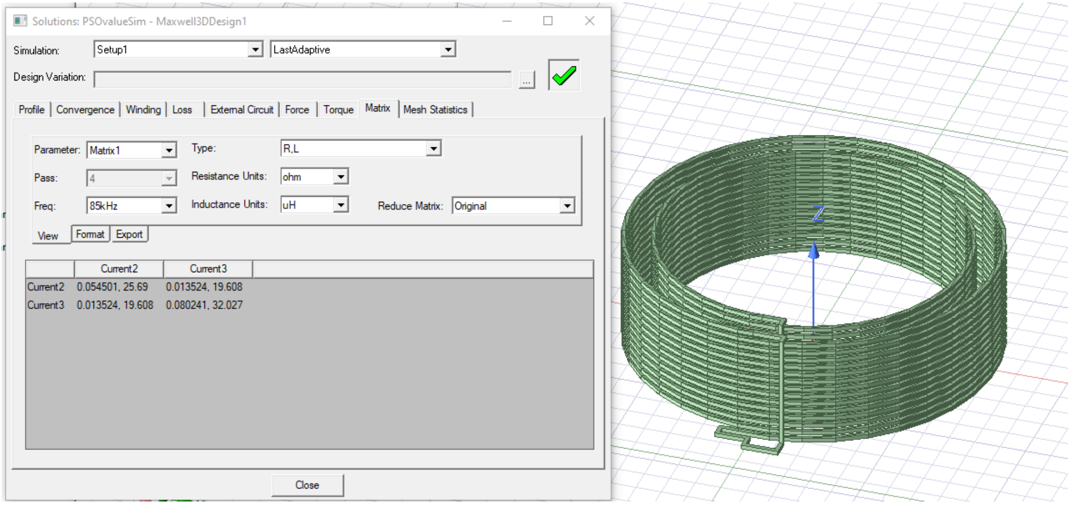


Figure 4.2: Primary and Secondary Voltage Comparison

.6



Solutions: PSOvalueSim - Maxwell3DDesign1

Simulation: Setup1 LastAdaptive

Design Variation:

Parameter: Matrix1

Type: R,L

Pass: 4

Resistance Units: ohm

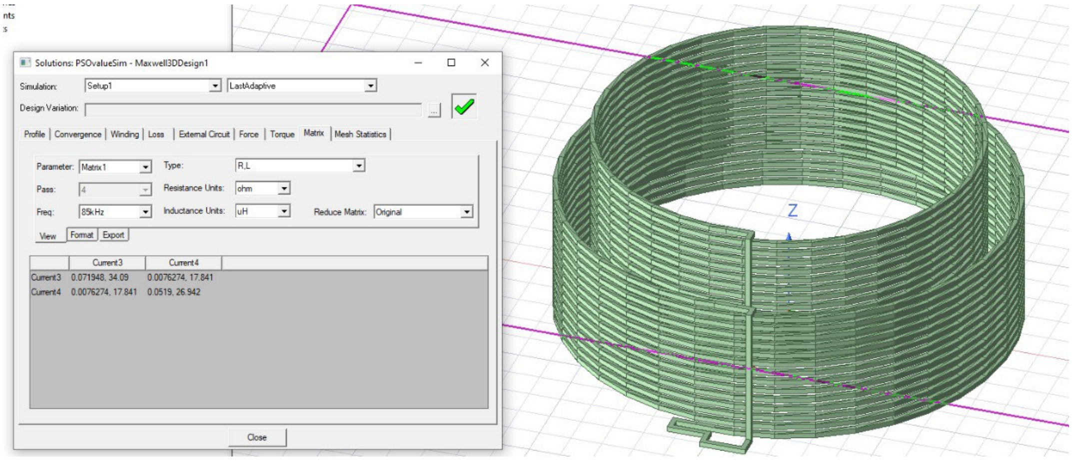
Freq: 85kHz

Inductance Units: uH

Reduce Matrix: Original

	Current2	Current3
Current2	0.054501, 25.69	0.013524, 19.608
Current3	0.013524, 19.608	0.080241, 32.027

Figure 4.3: Concentric Coil Geometry in Ansys Maxwell 3D



Simulation: Setup1 LastAdaptive

Design Variation:

Parameter: Matrix1

Type: R,L

Pass: 4

Resistance Units: ohm

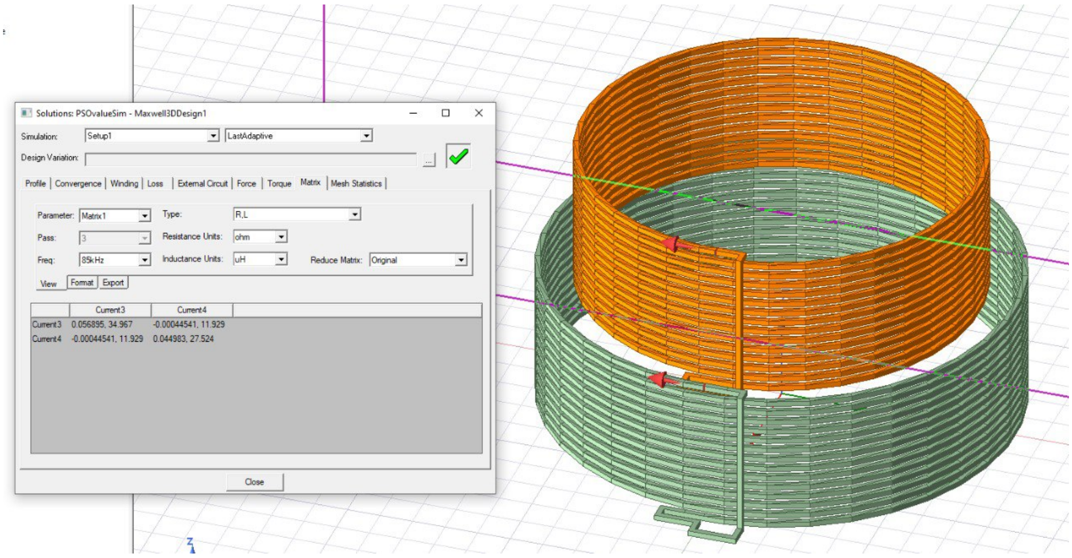
Freq: 85kHz

Inductance Units: uH

Reduce Matrix: Original

	Current3	Current4
Current3	0.071948, 34.09	0.0076274, 17.841
Current4	0.0076274, 17.841	0.0519, 26.942

Figure 4.4: Misalignment of 2 cm along Z-axis



Simulation: Setup1 LastAdaptive

Design Variation:

Parameter: Matrix1

Type: R,L

Pass: 3

Resistance Units: ohm

Freq: 85kHz

Inductance Units: uH

Reduce Matrix: Original

	Current3	Current4
Current3	0.056895, 34.967	-0.00044541, 11.929
Current4	-0.00044541, 11.929	0.044983, 27.524

Figure 4.5: Misalignment of 4 cm along Z-axis

4.2 Discussions

Finally, implementing inductance values and desired output power parameters, we construct a SIMULINK model of the system as it is depicted in 3.1. On that model, a 12V DC input source powers the system, which immediately is converted into AC since Inductive Power Transfer is possible only with AC. High frequency full-bridge inverter with operating frequency of 85kHz was designed using MOSFETs. Then a mutual inductance model was created based on dependent voltage source representation. After connecting primary and secondary sides, a rectifying circuit was added to finally be able to charge the battery as well as a filtering circuit for smoothing signals.

Overall, the mutual inductance design was successfully operating and 12V after inverter was almost fully transferred into the secondary side which can be seen in 4.2. 1.746A was the measured current at the input, which was about 1.429A at the output. Voltage at the output was about 11.4V. Therefore, it can be seen that input power was about 21W, while output power was 16.3W. Efficiency will be approximately 77.63%. Such relatively low efficiency can be caused at every step of the process starting from the PSO algorithm, where increasing the number of iterations would significantly increase the preciseness of the optimization. Additionally, in ANSYS Maxwell 3D, not perfect geometry was implemented for simulation and inductance calculations, therefore obtained mutual inductance value can still be improved in terms of preciseness. Lastly, in MATLAB SIMULINK modeling, parameter values were calculated manually such as filtering circuit, where a ripple factor of 3% was firstly assumed and then used for calculation of both capacitor and inductor values. Moreover, simulation errors are also possible within the MATLAB environment.

This work presents the design of an inductive power transfer (IPT) system with concentric coil geometry with simulation and analysis carried out within MATLAB and ANSYS environments. The efficiency in the simulated system was 77.63% under perfect alignment, decreasing to 75.44% and 67.74% when there was 2 cm and 4 cm misalignment, respectively. Experimental verification in air and salt water was used to show system reliability and achieved efficiencies of 71.47% and 74.57%, respectively. In misalignment tests, the efficiency decreased from 69.22% to 30.03% in air and from 62.47% to 50.55% in salt water as coil displacement was increased. Although performance decreased with complete misalignment, the system remained stable for partial displacement, indicating towards its suitability for dynamic coil position settings, i.e., underwater deployments. With a consideration for low-power operation, this work opens doors for the design of future efficient and high-power IPT systems.

Chapter 5

Experimental Setup and Results

This chapter presents the experimental design, hardware setup, testing procedures, and performance analysis of the wireless power transfer system developed using concentric coils. The focus lies on evaluating the system in both air and salt water media, analyzing effects of coil misalignment, and quantifying overall performance including system efficiency and mutual inductance.

5.1 Hardware Implementation

The hardware setup involved constructing a high-frequency inverter circuit, fabricating transmitting and receiving concentric coils, and integrating a high-frequency rectification and filtering stage. The inverter design was implemented on a breadboard, which, while sufficient for prototyping, may introduce instability due to loose connections and parasitic elements such as stray capacitance and inductance. In order to fabricate the desired inverter, different circuit designs were studied and all necessary components were ordered such as optocoupler(6N137), Schmitt trigger(SN74AC14N), not gates, MOSFETs(IRF3415) and driver for mosfets(HIP4081AIPZ). It was designed in such a way that two input sources are required: one for feeding electronics inside and another for overall circuit supply(feed from high side mosfets). Moreover, a PWM signal for excitation of mosfets is generated with ARDUINO UNO board, which can provide high-frequency signals with an amplitude of 5V.

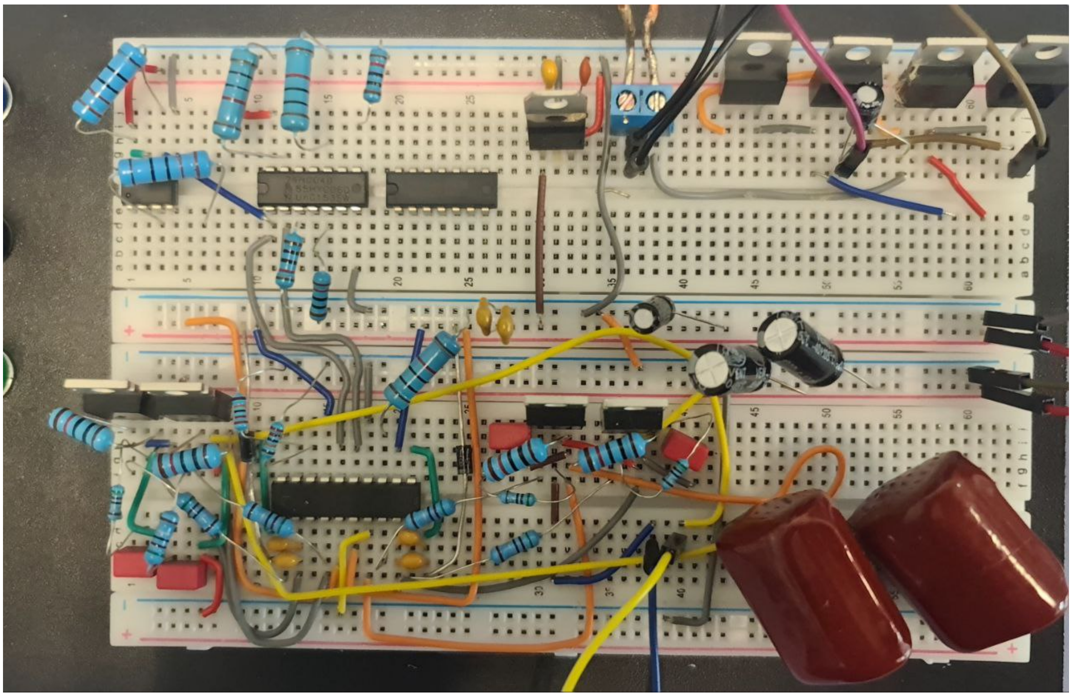


Figure 5.1: HF Inverter Circuit

Next step was to design coils. Two concentric circular coils were fabricated with diameters of approximately 9.4cm and 9.0cm, which were taken from PSO results. Stranded copper wire with a diameter of 0.1mm and 160 strands was glued around a solid plastic. The self-inductances were measured using an LCR meter and found to be 27 µH and 19 µH, respectively.

Figure 5.2: Designed Concentric Coils

Based on the measured inductances, the required compensation capacitor values were computed using:

$$C = \frac{1}{(2\pi f)^2 L} \tag{5.1}$$

where $f = 85$ kHz is the operating frequency. This yields:

- For $L = 27\ \mu H$: $C \approx 124$ nF
- For $L = 19\ \mu H$: $C \approx 176$ nF

Common values of capacitors provided 133nF and 180nF.

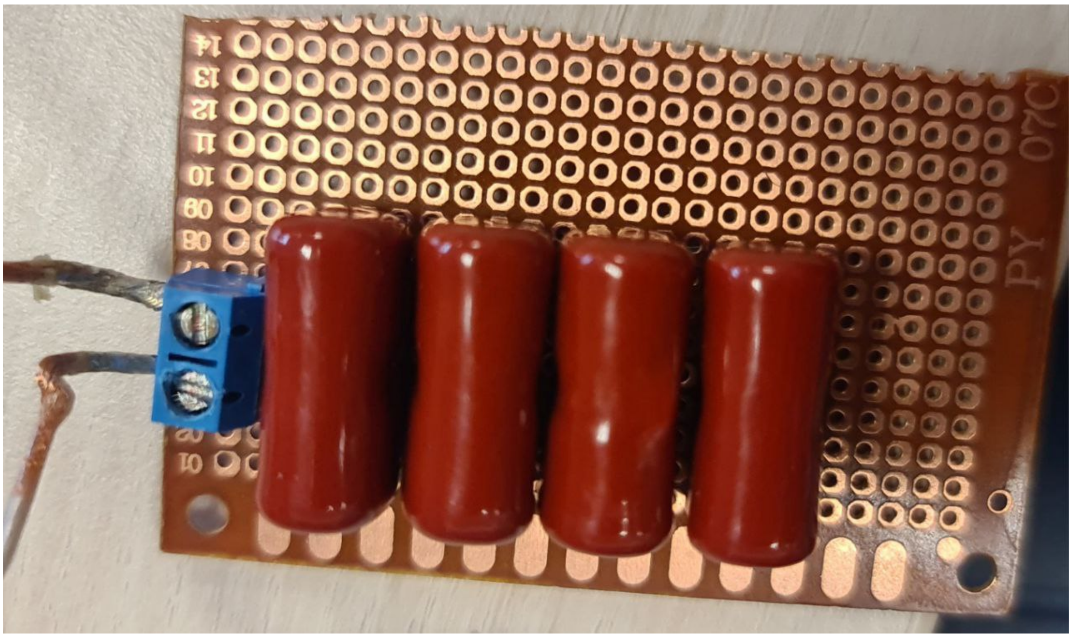


Figure 5.3: Compensation Capacitor Soldering

These capacitors were achieved by soldering several lower-valued capacitors in parallel. Namely, 4 capacitors with a 33nF were used in parallel for the primary compensation network and an additional 47nF was added in parallel for the secondary side compensation network. A full-wave rectifier was constructed using four diodes(Vishay MBR1635-E3/45) in the same breadboard and the same potential inaccuracies apply for the rectifier as well. High frequency rectifier was followed by a low-pass LC filter with a custom-wound 6–7 turn inductor on a metallic core (47–50 µH) and a 47 µF capacitor rated at 25 V for smoothing the DC output. The power supply provided 12 V at 1 A, while the inverter was driven by a 5 V, 85 kHz PWM signal generated using an Arduino Uno, passed through an optocoupler for isolation. Inside electronics were fed by 0.1A and 12V, which was transformed into 5V through voltage regulator(LM7805).

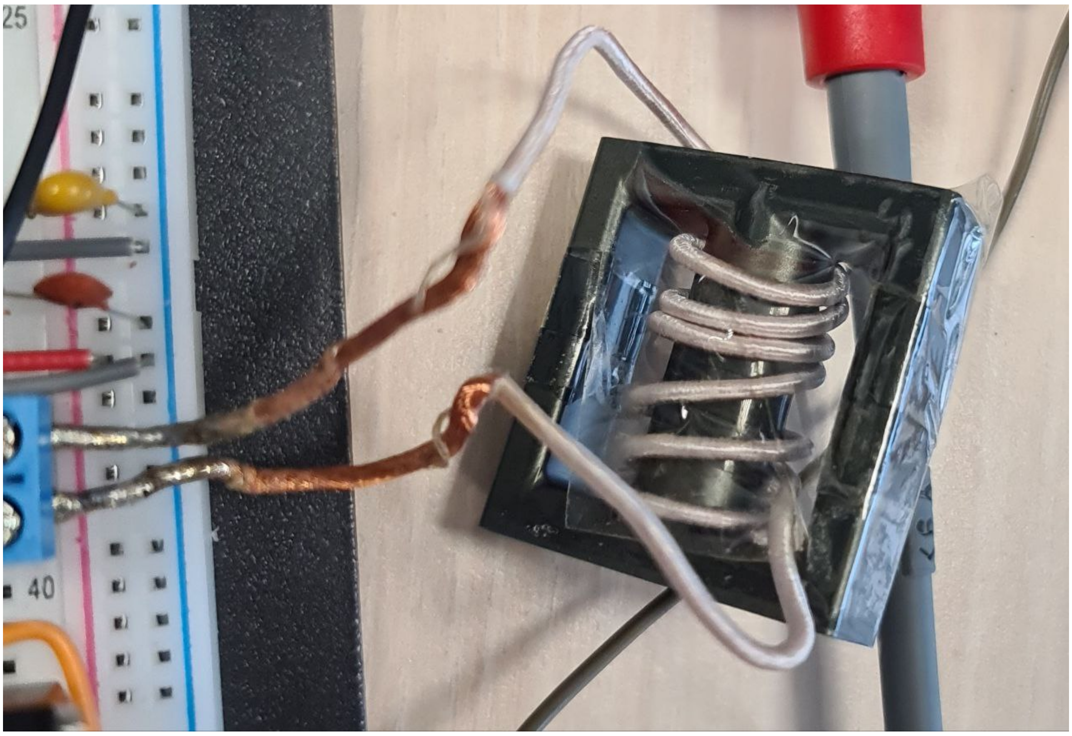


Figure 5.4: Filtering Inductor

The overall setup was following for air-medium tests:

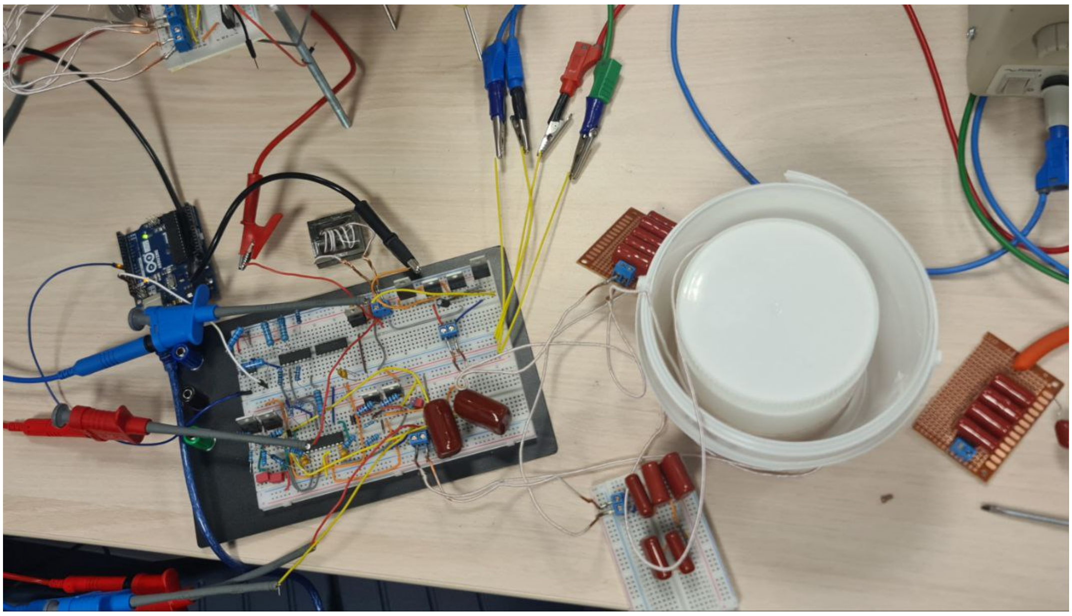


Figure 5.5: Final Setup for IPT using concentric coils

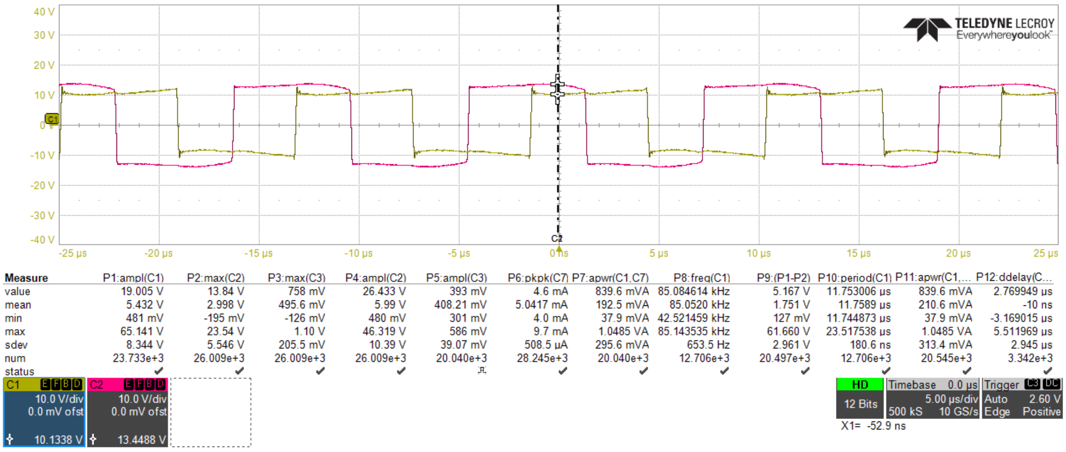
Measurement instruments included:

- **HDO8108R Oscilloscope:** Used for capturing high-resolution voltage and current waveforms.
- **BK PRECISION 8600:** A programmable DC electronic load for precise current draw. It was set to 1A and acted as a storage element in the system.
- **EL302RT Triple Power Supply:** Provided regulated input power to the inverter and other components.

5.2 Performance Testing in Air and Water

Initial testing was done in air with fully aligned coils. For an underwater testing sealing was required since wire that was used has only nylon insulation, which is water resistant rather than waterproof. In order to accomplish that sealing, both coils were wrapped around several times by a cling film and fixed by using insulation tape. It is certainly not the best option for sealing, however for short-period underwater performance the method that was used is sufficient. The system achieved 10.85 V DC at 1 A output, while the power supply indicated 10.85 V at 1.448 A, resulting in a system efficiency of 71.47%.

Figure 5.6: Underwater Testing Condition



Measure	P1:ampl(C1)	P2:max(C2)	P3:max(C3)	P4:ampl(C2)	P5:ampl(C3)	P6:pkpk(C7)	P7:apwr(C1,C7)	P8:freq(C1)	P9:(P1-P2)	P10:period(C1)	P11:apwr(C1,...	P12:ddelay(C...
value	19.005 V	13.84 V	758 mV	26.433 V	393 mV	4.6 mA	839.6 mVA	85.084614 kHz	5.167 V	11.753006 µs	839.6 mVA	2.769949 µs
mean	5.432 V	2.998 V	495.6 mV	5.99 V	408.21 mV	5.0417 mA	192.5 mVA	85.0520 kHz	1.751 V	11.7589 µs	210.6 mVA	-10 ns
min	481 mV	-195 mV	-126 mV	480 mV	301 mV	4.0 mA	37.9 mVA	42.521459 kHz	127 mV	11.744873 µs	37.9 mVA	-3.169015 µs
max	65.141 V	23.54 V	1.10 V	46.319 V	586 mV	9.7 mA	1.0485 VA	85.143535 kHz	61.660 V	23.517538 µs	1.0485 VA	5.511969 µs
sdev	8.344 V	5.546 V	205.5 mV	10.39 V	39.07 mV	508.5 µA	295.6 mVA	653.5 Hz	2.961 V	180.6 ns	313.4 mVA	2.945 µs
num	23.733e+3	26.009e+3	26.009e+3	26.009e+3	20.040e+3	28.245e+3	20.040e+3	12.706e+3	20.497e+3	12.706e+3	20.545e+3	3.342e+3
status	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓

C1 E F B D
10.0 V/div
0.0 mV ofst
10.1338 V

C2 E F B D
10.0 V/div
0.0 mV ofst
13.4488 V

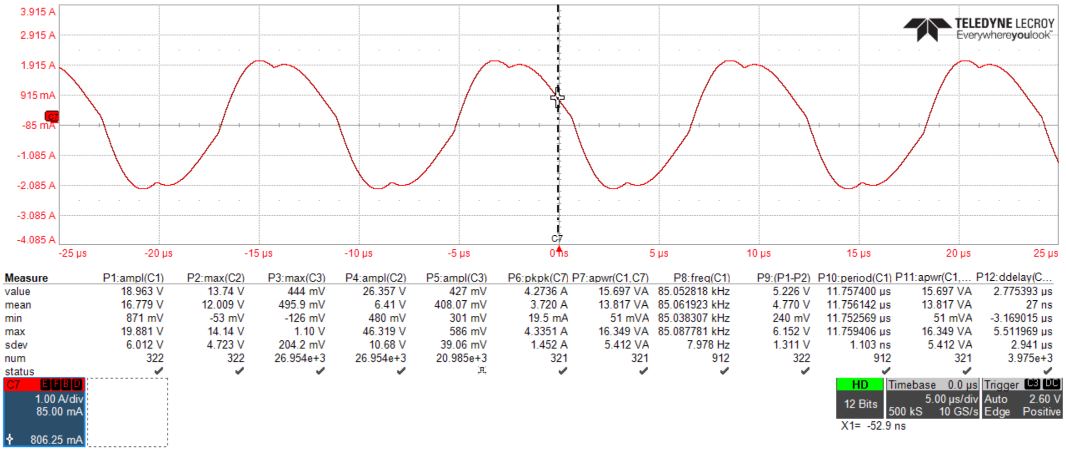
HD
12 Bits

Timebase 0.0 µs
5.00 µs/div
500 kS 10 GS/s

Trigger C3 DC
Auto 2.60 V
Edge Positive

X1= -52.9 ns

Figure 5.7: Primary and Secondary Side AC Voltages



Measure	P1:ampl(C1)	P2:max(C2)	P3:max(C3)	P4:ampl(C2)	P5:ampl(C3)	P6:pkpk(C7)	P7:apwr(C1,C7)	P8:freq(C1)	P9:(P1-P2)	P10:period(C1)	P11:apwr(C1,...	P12:ddelay(C...
value	18.963 V	13.74 V	444 mV	26.357 V	427 mV	4.2736 A	15.697 VA	85.052818 kHz	5.226 V	11.757400 µs	15.697 VA	2.775393 µs
mean	16.779 V	12.009 V	495.9 mV	6.41 V	408.07 mV	3.720 A	13.817 VA	85.061923 kHz	4.770 V	11.756142 µs	13.817 VA	27 ns
min	871 mV	-53 mV	-126 mV	480 mV	301 mV	19.5 mA	51 mVA	85.038307 kHz	240 mV	11.752569 µs	51 mVA	-3.169015 µs
max	19.881 V	14.14 V	1.10 V	46.319 V	586 mV	4.3351 A	16.349 VA	85.087781 kHz	6.152 V	11.759406 µs	16.349 VA	5.511969 µs
sdev	6.012 V	4.723 V	204.2 mV	10.68 V	39.06 mV	1.452 A	5.412 VA	7.978 Hz	1.311 V	1.103 ns	5.412 VA	2.941 µs
num	322	322	26.954e+3	26.954e+3	20.985e+3	321	321	912	322	912	321	3.975e+3
status	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓

C7 E F B D
1.00 A/div
85.00 mA
806.25 mA

HD
12 Bits

Timebase 0.0 µs
5.00 µs/div
500 kS 10 GS/s

Trigger C3 DC
Auto 2.60 V
Edge Positive

X1= -52.9 ns

Figure 5.8: Primary Side Current

5.3 Calculation of Efficiency and Mutual Inductance

The efficiency was calculated based on DC power at input and output:

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100 = \frac{V_{\text{out}} \cdot I_{\text{out}}}{V_{\text{in}} \cdot I_{\text{in}}} \times 100$$

Mutual inductance was estimated using the relation between peak values of voltage and current:

$$M = \frac{V_2^{\text{peak}}}{\omega I_1^{\text{peak}}}$$

Where $\omega = 2\pi \times 85\,000 = 534070$ rad/s

In this case: Given $V_2^{pp} = 26.4\,\text{V}$, $I_1^{pp} = 4.28\,\text{A}$

$$V_2^{peak} = 13.2 \text{ V}, \quad I_1^{peak} = 2.14 \text{ A}$$

$$M = \frac{13.2}{534070 \cdot 2.14} \approx 11.55\ \mu\text{H}$$

5.4 Results in Air and Underwater Conditions

Table 5.1: Performance Metrics in Air and Underwater

Medium	V_{in} (V)	I_{in} (A)	V_{out} (V)	I_{out} (A)	η (%)	M (μH)
Air	10.85	1.448	10.85	1.00	71.47	11.68
Water	10.99	1.448	10.78	1.00	67.74	9.55

5.5 Misalignment Analysis

Air Medium

Table 5.2: Misalignment Results in Air

Position	V_{in} (V)	I_{in} (A)	V_{out} (V)	I_{out} (A)	η (%)	M (μH)
Fully aligned	11.46	1.00	7.93	1.00	69.22	9.96
1 cm upward	9.76	1.00	5.66	1.00	56.61	7.67
2 cm upward	8.44	1.00	4.47	1.00	52.96	6.04
4 cm upward	7.29	1.00	2.19	1.00	30.03	4.18

Salt Water Medium

Table 5.3: Misalignment Results in Salt Water

Position	V_{in} (V)	I_{in} (A)	V_{out} (V)	I_{out} (A)	η (%)	M (μH)
Fully aligned	10.92	1.00	6.82	1.00	62.47	8.57
1 cm upward	9.49	1.00	5.32	1.00	56.03	7.39
2 cm upward	7.28	1.00	3.68	1.00	50.55	5.90

For comparison, maximum efficiency of 83.57 % at power rating of 38.3W was achieved by [28], with utilizing planar coils.

These results confirm that increasing vertical misalignment significantly reduces the output voltage and overall system efficiency, with the salt water medium slightly mitigating performance losses likely due to better electromagnetic coupling compared to air. Sealing of the coils for underwater testing was done using plastic wrap and insulating tape to ensure short-term water resistance.

Chapter 6

Conclusion

This research paper demonstrated a one potentially optimal design of inductive power transfer technology with utilization of concentric coil geometry. Simulation and analysis within Matlab and ANSYS environment clearly presented system's high efficiency. The performance of an Inductive Power Transfer (IPT) system was investigated under simulated and experimental conditions, focusing on power transfer efficiency analysis, misalignment impact, and the effect of the medium (air vs. underwater). Both simulation and experimental results highlighted the suitability of the system for wireless power transfer applications with slight differences in performance across the test conditions.

In the simulation, the system had an efficiency of 77.63 % and power transfer from the primary to the secondary side was nearly complete. However, some conditions like optimization process in the Particle Swarm Optimization (PSO) algorithm, the not-so-perfect geometry in ANSYS Maxwell for calculating mutual inductance, and assumptions while modeling in MATLAB SIMULINK were the causes of the relatively lower efficiency. But the model of mutual inductance operated as expected, and simulation misalignment tests suggested that the system was stable to coil displacement and demonstrated the potential for practical application in environments where coil positions may be variable, such as underwater.

Experimental data in air and salt water duplicated the simulation data. In air, the system was 69.22% efficient when the coils were in their maximum alignment and dropped precipitously as misalignment increased to 30.0% when misaligned 4 cm in upward displacement. In salt water, the system also had the same trend as its efficiency reduced from 62.47% to 50.55% as misalignment increased. The system's performance in salt water was slightly less than in air, which suggests that the medium can influence power transfer efficiency, although the system performed in both cases.

The results of this work underscore the importance of precise coil alignment to ensure optimum power transfer efficiency. However, the system displayed strength against misalignments within a small amount, particularly for real-world environments such as underwater wireless power transfer. The results further show that there is a need for optimization, particularly in geometry and algorithms of power optimization, to deliver increased efficiency for high-power application.

Lastly, while the IPT system functioned efficiently in the simulation and experimental examples, system design enhancement, alignment accuracy, and high-power testing need to be accomplished for the system to realize full potential in real applications. The future studies will seek to refine the design parameters and examine the behavior of the system in more complex environments in order to further evaluate its performance in real-world applications. Nevertheless, the paper focused on relatively low power applications, thus the same simulation with proper experimental setup for higher power rates is further suggested to study. Eddy current losses were considered as an additional radiation resistance and within the same block of coil resistance due to series connection.

Bibliography

[1] Tianze Kan et al. “Design and Analysis of a Three-Phase Wireless Charging System for Lightweight Autonomous Underwater Vehicles”. In: *IEEE Transactions on Power Electronics* 33.8 (2018), pp. 6622–6632. DOI: `10.1109/TPEL.2017.2757015`.

[2] Aganti Mahesh, Bharatiraja Chokkalingam, and Lucian Mihet-Popa. “Inductive Wireless Power Transfer Charging for Electric Vehicles–A Review”. In: *IEEE Access* 9 (2021), pp. 137667–137713. DOI: `10.1109/ACCESS.2021.3116678`.

[3] Lei Wang et al. “Mutual Inductance Identification of IPT System Based on Soft-Start Process”. In: *IEEE Transactions on Power Electronics* 37.6 (2022), pp. 7504–7517. DOI: `10.1109/TPEL.2022.3142289`.

[4] Chakridhar Reddy Teeneti et al. “Review of Wireless Charging Systems for Autonomous Underwater Vehicles”. In: *IEEE Journal of Oceanic Engineering* 46.1 (2021), pp. 68–87. DOI: `10.1109/JOE.2019.2953015`.

[5] H. Hughes and L. A. Gish. “Inductive recharging for a small commercial autonomous underwater vehicle”. In: *OCEANS 2017 - Anchorage*. 2017, pp. 1–8.

[6] Adilkhan Kapanov et al. “Impact Analysis of Sea Environment on Capacitive Power Transfer Systems: Equivalent Circuit Parameters and Performance Analysis”. In: *2024 13th International Conference on Renewable Energy Research and Applications (ICRERA)*. 2024, pp. 601–605. DOI: `10.1109/ICRERA62673.2024.10815205`.

[7] Trong-Duy Nguyen et al. “Feasibility study on bipolar pads for efficient wireless power chargers”. In: Mar. 2014, pp. 1676–1682. ISBN: 978-1-4799-2325-0. DOI: `10.1109/APEC.2014.6803531`.

[8] Sampath Jayalath and Azeem Khan. “Design, Challenges, and Trends of Inductive Power Transfer Couplers for Electric Vehicles: A Review”. In: *IEEE Journal of Emerging and Selected Topics in Power Electronics* 9.5 (2021), pp. 6196–6218. DOI: `10.1109/JESTPE.2020.3042625`.

[9] Zhengchao Yan et al. “Eddy current loss analysis of underwater wireless power transfer systems with misalignments”. In: *AIP Advances* 8 (Oct. 2018), p. 101421. DOI: 10.1063/1.5040271.

[10] Lei Yang et al. “A review of underwater inductive wireless power transfer system”. In: *IET Power Electronics* 17.8 (2024), pp. 894–905. DOI: https://doi.org/10.1049/pel2.12456. eprint: https://ietresearch.onlinelibrary.wiley.com/doi/pdf/10.1049/pel2.12456. URL: https://ietresearch.onlinelibrary.wiley.com/doi/abs/10.1049/pel2.12456.

[11] Zhengchao Yan et al. “Underwater wireless power transfer system with a curly coil structure for AUVs”. In: *IET Power Electronics* 12.10 (2019), pp. 2559–2565. DOI: https://doi.org/10.1049/iet-pel.2018.6090. eprint: https://ietresearch.onlinelibrary.wiley.com/doi/pdf/10.1049/iet-pel.2018.6090. URL: https://ietresearch.onlinelibrary.wiley.com/doi/abs/10.1049/iet-pel.2018.6090.

[12] Tianze Kan et al. “A Rotation-Resilient Wireless Charging System for Lightweight Autonomous Underwater Vehicles”. In: *IEEE Transactions on Vehicular Technology* 67.8 (2018), pp. 6935–6942. DOI: 10.1109/TVT.2018.2836988.

[13] Ze-song Li et al. “Design considerations for electromagnetic couplers in contactless power transmission systems for deep-sea applications”. In: *Journal of Zhejiang University - Science C* 11 (Oct. 2010), pp. 824–834. DOI: 10.1631/jzus.C0910711.

[14] Mohammed Sabith. “Underwater Wireless Power Transfer for Maritime Applications”. In: *International Journal of Engineering Research and* V9 (June 2020). DOI: 10.17577/IJERTV9IS060335.

[15] Le Yu et al. “Review of Crucial Problems of Underwater Wireless Power Transmission”. In: *Electronics* 12.1 (2023). ISSN: 2079-9292. DOI: 10.3390/electronics12010163. URL: https://www.mdpi.com/2079-9292/12/1/163.

[16] Haibing Wen et al. “A novel concentric circular ring structure applied in AUV’s inductive power transfer system for resisting the disturbance of ocean current”. In: *AIP Advances* 8.11 (Nov. 2018), p. 115027. ISSN: 2158-3226. DOI: 10.1063/1.5042791. eprint: https://pubs.aip.org/aip/adv/article-pdf/doi/10.1063/1.5042791/12883354/115027_1_online.pdf. URL: https://doi.org/10.1063/1.5042791.

[17] Jing Zhou et al. “Design Considerations for a Self-Latching Coupling Structure of Inductive Power Transfer for Autonomous Underwater Vehicle”. In: *IEEE Transactions on Industry Applications* 57.1 (2021), pp. 580–587. DOI: 10.1109/TIA.2020.3029020.

[18] Viktor Bana et al. "Underwater wireless power transfer for maritime applications". In: *2015 IEEE Wireless Power Transfer Conference (WPTC)*. 2015, pp. 1–4. DOI: 10.1109/WPT.2015.7139142.

[19] Chu, Son et al. "Fields and coupling between coils embedded in conductive environments". In: *EPJ Appl. Metamat.* 5 (2018), p. 2. DOI: 10.1051/epjam/2017012. URL: https://doi.org/10.1051/epjam/2017012.

[20] Jongwook Kim et al. "An Efficient Modeling for Underwater Wireless Power Transfer Using Z-Parameters". In: *IEEE Transactions on Electromagnetic Compatibility* 61.6 (2019), pp. 2006–2014. DOI: 10.1109/TEMC.2019.2952320.

[21] Siqi Li and Chunting Chris Mi. "Wireless Power Transfer for Electric Vehicle Applications". In: *IEEE Journal of Emerging and Selected Topics in Power Electronics* 3.1 (2015), pp. 4–17. DOI: 10.1109/JESTPE.2014.2319453.

[22] Kehan Zhang et al. "A New Coil Structure to Reduce Eddy Current Loss of WPT Systems for Underwater Vehicles". In: *IEEE Transactions on Vehicular Technology* PP (Nov. 2018), pp. 1–1. DOI: 10.1109/TVT.2018.2883473.

[23] Sadjad Shafiei et al. "Design and Implementation of Underwater Inductive Power Transfer Systems With An Accurate Eddy Current Loss Model Approach". In: *IEEE Transactions on Industry Applications* 61.2 (2025), pp. 3359–3370. DOI: 10.1109/TIA.2024.3524480.

[24] Sudeep Pyakuryal and Mohammad Abdul Matin. "Filter Design for AC to DC Converter". In: 2013. URL: https://api.semanticscholar.org/CorpusID:6279721.

[25] Xiaohui Hu and R. Eberhart. "Solving constrained nonlinear optimization problems with particle swarm optimization". In: *Citeseer* 2002 (Jan. 2002), pp. 203–206.

[26] Mahamad Alam. *Particle Swarm Optimization: Algorithm and its Codes in MATLAB*. Mar. 2016. DOI: 10.13140/RG.2.1.4985.3206.

[27] Seyed Saeid Heidari Yazdi et al. "A Wireless Charging System Based on a DR-IPT to Power a UAV From Distribution Poles". In: *IEEE Transactions on Industry Applications* 59.6 (2023), pp. 7757–7770. DOI: 10.1109/TIA.2023.3307082.

[28] Seyed Saeid Heidari Yazdi et al. "Analyzing Sea Environment's Effects on Inductive Power Transfer Systems: Equivalent Circuit Parameters and Performance Analysis". In: *2024 IEEE International Conference on Environment and Electrical Engineering and 2024 IEEE Industrial and Commercial Power Systems Europe*. 2024, pp. 1–6. DOI: 10.1109/EEEIC/ICPSEurope61470.2024.10751266.