Foreign Object Detection in Wireless Power Transfer

Capstone Report

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Abstract:

This project explores the phenomenon of Foreign Object Detection (FOD) in Wireless Power Transfer (WPT) systems with a particular emphasis on Metallic Object Detection (MOD) in Inductive Power Transfer (IPT) for applications such as electric vehicle charging. Although WPT enhances convenience and safety by minimizing physical connections, the presence of foreign objects inserted between the transmit and receive coils presents major issues, including efficiency loss, possible damage to objects, and safety hazards. This study introduces a sensor-based MOD system using a novel arrangement of sensing coils placed in close proximity to the transmitting coil. The detection principle is based on the examination of induced voltage changes across the symmetrical detection coils. The metallic object presence perturbs the magnetic field, inducing a detectable difference in induced voltage between the symmetrical coils. The report specifies the sensing coil design to be proposed, such as coil positioning and size, and the corresponding MOD circuit that is to be used to filter, amplify, and rectify induced voltage signals for safe detection by a microcontroller unit.

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Chapter 1

Introduction

Wireless Power Transfer (WPT) technology introduced by Nikola Tesla is getting more attention in recent years. Possibility of removing wires from charging process makes it more comfortable to use by people and safe as human do not need to interact with any power cables. [1, 2] For these reasons, different wireless charging systems are developing around the world for numerous applications such as biomedical devices, electric vehicles etc. [3, 4] Moreover, wireless power transfer can be achieved using different methods which are mostly dependent on the transmission distance and principle of working. Mainly, WPT classified as near-field and far-field. Near-field methods involve magnetic field and electric field to transmit power. When far field methods are focused on microwaves and radio waves. [2, 5]

Technique that will be investigated in this research is inductive power transfer (IPT) which is based on ampere's law and electromagnetic induction. [1, 2] This method uses two loosely coupled coils where one of the coils creates time varying magnetic field which leads to voltage inducing in a second coil. IPT is promising approach in wireless charging. It is capable to deliver power with high efficiency which can be seen from results in different experiments implemented for charging electric vehicles. [3, 6] The WiTricity corporation developed using MIT development published their development kit capable of delivering 3.3 kW with 90% efficiency. [3] Another WPT system based on magnetic induction was developed by Oak Ridge National Laboratory for 3 kW showing 90% efficiency. [3] Showa Aircraft Company from Japan built 30 kW wireless charging system at 22 kHz frequency with coil distances of 14 cm reaching 92% efficiency. [3] Despite these advancements in IPT, there are still a lot of difficulties in integrating it to industries, for example, adjusting system to industry standards, optimizing for different uses, misalignment tolerance, cost effectiveness. [1, 3, 5, 7] Furthermore, in this research it is assumed that concept of a system will be used for electric vehicle. Considering charging of EVs, charging can be categorized to static and dynamic charging. The main difference is that in dynamic mode receiving side can be charged during motion. [5] In this case, static charging mode is chosen for study.

Designing IPT system able to transmit power with satisfied efficiency is only part of the solution. Next step is to make it usable for people, for that different cases under different conditions must be considered. One of the possible problem that could emerge is appearance of foreign object between transmitting and receiving side. [8, 9, 10] Depending on the type of an object it can negatively affect to charging process or object itself can get damage. To make charging process safe and prevent other issues, foreign object detection (FOD) is introduced. [9, 11] Foreign objects can be classified as follows: metal objects and living objects. [8, 10] Metal objects such as coins or keys can affect magnetic field between two coils resulting in output power decrease, eddy current loss, mutual inductance change. [12] Living objects also can cause such problems, but main concern with living objects is damage to health by generated magnetic field.[9, 10] It is important to make sure that any foreign object is not present and exposed during charging process. [13] To deal with this, foreign object detection system will be proposed and tested using optimized low power IPT system experimentally. Low power IPT system will be designed and tested on li-ion battery before working with FOD.

Regarding IPT system, on transmitting side, DC voltage source, high frequency inverter, compensating capacitor and coil will be placed. [14] On receiving side, receiving coil, compensating capacitor, rectifier to deliver DC voltage and battery will be located. [14] Coils are planar spring coil. Parameters of the system will be identified using particle swarm optimization (PSO) algorithm to adjust them to needed output power and maintain good efficiency. [**psoipt**, 14] PSO algorithm is used to identify coil parameters for design. Parameters such as output power, power electronics characteristics, input voltage are predefined. [**psoipt**] Based on these parameters, possible range for coil parameters and using mathematical model of the system most optimal solution is found.[15]

FOD system will be designed for metal objects. Metal object detection (MOD) was chosen because metal objects appear a lot more comparing to living objects and have big impact on system performance. [16, 17, 18] Metallic foreign object detection methods are divided into three categories: sensor-based detection, parameter detection and sensing pattern-based detection.[9] First method works by identifying varying in different parameters such as temperature, pressure via sensors mounted on transmitting or receiving sides. [9, 10] Second method uses electrical parameters like self-inductance, current, input impedance or output power to identify presence of metal object. [9] Various relationships are derived between parameters and presence of the objects. Third method that will be implemented in this project works by using additional detection coil. [9] Detection coil can be in different shapes and mostly have repeating pattern to identify precisely metal object (MO). [16, 17, 19] Detection coil is mounted on the wireless charging system coupler. [16]

Sensing pattern based detection techniques are the most common approach to detecting metal objects (MOs) in wireless power transfer systems on the principle that MOs interfer the magnetic field. They are typically founded on detection coils or arrays that are placed in a way close to the power transmitter (TX). The basic principle is that an MO alters the electrical properties of these detection coils, primarily their quality factor and inductance, through inductive coupling. Small MOs are hard to detect since their influence on a large detection coil may be small. Thus, arrays of small detection coils are typically used to enhance sensitivity thus that a small object causes a little local change. Another problem is misalignment of the receiver coil, which also affects inductance; however, misalignment tends to affect all detection coils, whereas a small mutual oscillation will affect mostly only adjacent coils, making detection easier.[8]

There are several specific methods in this category. Measurement of the direct variation in inductance is popular, with research suggesting that parallel resonant circuits provide greater sensitivity to MOs and improved noise immunity than series resonant circuits. Optimization of the coil geometry, the utilization of shapes like double-D or clover-leaf shapes instead of conventional rectangles, can be utilized to enhance sensitivity across the detection area. Another technique is a variation in equivalent resistance of the detection coil or its pulse-excited response; the presence of an MO causes a shift in the rate or amplitude of response signal decay. Impedance changes, impulse response, and resistance changes due to temperature changes according to the eddy current in the MO can serve as indicators.[8]

Also, the process of identification can be founded on variations in the voltage generated in the detection coils. [20] Passive methods utilize the main power transfer field; symmetrical pairs of coils, which are arranged to have zero net induced voltage if there is no MO, will produce a voltage signal if an MO is in the area of the field. Active methods use a separate transmitter and receiver coil pair, independent of each other, at another high frequency (e.g., 1-10 MHz). An MO interrupts this decoupling, causing a voltage to be induced in the receiver side. Passive and active voltage based techniques can both be prone to blind zones where an MO may not produce a detectable signal. Resonance circuits play a significant role in amplifying the impedance changes introduced by MOs, increasing detection sensitivity, especially when the detection coils possess a high quality factor.[8]

Proposed detection coil will have symmetrical configuration. One set of coils are arranged on top of the transmitting coil in one axis. Resonating detection coil at different frequency allows to not disturb work of main system. [9, 18, 19] The working principle is based on induced voltage, by analyzing this parameter object is detected. [9, 11] Calculated difference in induced voltage between symmetrical coils will determine object. Induced voltage between coils is proportional to the mutual inductance, considering that directions of two set of coils will be different. location of metal object can be identified. Any changes in mutual inductance of any coil in the set means presence of foreign object in charging area. Number of changes in overall each set will be equal to number of metal objects. Mutual inductance change and their behavior will be tested in ANSYS Maxwell. [17]

1.1 Ethical and Professional Responsibilities

- **Ethical Responsibility:**
  This project considers ethical issues that can arise after completing the system. One of them is safety. System needs to be designed in such way that it will have minimum affect on people and somehow interact with environment as living object detection will not be included. To prevent situations when people can be damaged because of generated magnetic field or objects are overheated, system must have protection, labeling and built according to standards of different communities.

  The problem arises with the data collected by MOD systems. These systems often collect information about the presence and type of metal objects, which may unintentionally include personal items. Ethical responsibility requires that this data be treated with strict confidentiality and used only for security purposes. Data security needs to be considered and prevention of unauthorized access needs to be implemented.

  Also, to address this issue and fairness of the system, many tests must be done under wide range of conditions. Thus it will not behave differently in other cases. Conditions can be derived from ethical reviews, responses from potential users.

- **Informed Judgments:**
  To provide system that is well-developed and ensures all aspects that can subjected to influence multiple approaches are involved. First one is comprehensive literature review to identify best practices and consider all scenarios. This approach can give foundation for well-informed decisions. In addition, simulations in special applications such as Matlab or Ansys Electronics can show technical issues and aspects of proposed system. Performance of the system, reaction to sudden changes and affect of system to other objects will be taken into account by testing and data gathering.

  Moreover, societal factors are also be considered. Wireless charging systems often used in public areas near stations or buildings. Safetu in such places is crucial. Safety guidelines and standards for these situations will be incorporated using international and industry rules.

  Meetings with safety regulators, industry people will help ensure that the system design addresses all safety concerns. An iterative design process will be important to make informed choices. Initial designs will likely require modifications due to the fact that standards are varied everywhere. Metal object detection in IPT system primarily used in industries such as electric vehicle charging and public transportation. Communications with industry stakeholders such as manufacturers, users, and maintenance groups will provide useful insights into the practical and financial challenges of implementing the technology.

- **Global Context:**
  One advantage of this project is possibility of implemetation system across the world. Usage of electric vehicles in different continents allows integrating it to different countries. Building this system in regions with proper technological infrastructure can improve safety and promote wireless power transfer further. Regions with low level of technological development also can take benefit, wireless charging can introduce more accessible and safe way of power transferring. However, limited resouce availability and lack of regulations can make process of adoption a lot harder.

  Difference in cultural aspects also can have impact on use of the system. To identify these differences and possible problems, various local communities must be researched and corresponding changes made in the project.

  This project also promotes clean energy use and sustainable development. According to 17 goals of sustainable developments, clean energy and technological advancement are important parts of global society. Climate change and global warming are global issues caused by fossil fuels and other harmful things. Making any change in developing systems that use alternative sources of energy helps to solve mentioned issues.

  By considering these global contexts, the project can be designed and implemented in a way that maximizes its positive impact and addresses potential challenges in different parts of the world.

- **Economic Impact:**
  Economic aspect of metal object detection in IPT can have short term and long term perspectives. At the beginning, this system will require investmentrs from the side to manufacture them and provide accessibility. Manufacturing and testing processes will require workforse which means new job opportunities will be available.

  In long term perspective, this system will potentially reduce cost of power transferring. Current way of wired charging requires a lot of money to build stations and provide them everywhere. Moreover, human interaction with the charging process results in damage and frequent maintenance. Wireless power transfer system with MOD can eliminate human interaction and lower maintenance costs. Latter is achieved by MOD which do not allow objects to affect system performance.

  Developing MOD can enhance wireless charging development and foster this industry. This will lead to growth and economic prosperity. However, it is important to ensure simplicity of manufacturing process since some of the system parts are not easily available. And for example, fabrication of detection coil is not common in industry. This can lead to high prices at the start because of high demand and low supply. To solve it, investments and careful planning are needed. Proper parts that are available in most of the places must be chosen and fabrication also should be adjusted to different levels.

- **Environmental Impact:**
  Assessment of the environmental impact is crucial for this project because it uses electromagnetic induction and high voltage. Primary benefit from the MOD in IPT is that potential hazards such as overheating and electrical faults can be eliminated. Consequently, less environmental effect will be reached. Another concern is electromagnetic induction produced by coils. Living objects can get substantial damage in case of not being informed about it. And frequent interaction will lead to problems with health. People can be informed about this, but animals and birds cannot. To minimize impact to living objects protection is needed.

  Despite the fact that inductive type of charging progressed in efficiency, it still uses more energy than wired charging. Inductive charging still has losses in transferred power. Comparing to wired where everything is isolated, in this case magnetic field can have losses in air. As a result, inductive charging takes more energy to achieve the same result, resulting in higher power consumption.

  Manufacturing wireless chargers involves the use of different materials and energy sources, which contributes to their environmental impact. Components needed for IPT system, such as coils, and electronics materials, require raw materials and los ot processing. Size of resource consumption must be controlled and environment should not get harm.

- **Societal Impact:**
  As stated earlier MOD in IPT have huge impact on society and environment. It ensures safety of wireless charging process. Metal objects can be affected by magnetic field and heat in case of interaction, also they can damage charging station. To decrease this effect, system will be able to detect metal objects and stop chargin process or make corresponding changes. This makes charging more efficient and safe which benefit everyone.

  The project is in some sense is innovative, this technology already is implemented in various variants but is still seem as something unavailable in society. By bringing such technologies, industry will develop further. In addition, despite the fact that this project is aimed to be implemented for electric vehicles other industries also can use it. For instance, medical devices, consumer electronics. Power transferring is identical everywhere so adaptation of the system will be more easier.

Metal object detection enhances wireless power transfer production which leads to possibility of using it in our life. This can help some regions allow to build wireless charging stations if they are not able to make wired charging stations or use carbon vehicles.

Chapter 2

Methodology

2.1 Principle of Induced Voltage Method

The system proposed in this work will detect the presence of metal objects based on variation in induced voltage in detection coils. As Faraday's law states, when a conductor is placed in a time-varying magnetic field, voltage is induced, and it is proportional to the rate of change of magnetic flux [19]:

$$V = -\frac{d\phi}{dt} \tag{2.1}$$

According to this law, magnetic flux generated by transmitting side coil will result in induced voltage in detection coil. The induced voltage V_d can be expressed as follows where M_1 is mutual inductance between transmitting coil and detection coil, M_2 is mutual inductance between receiving coil and detection coil, I_1 and I_2 are currents flowing through transmitting and receiving coils respectively [10].

$$V_d = j\omega M_1 I_1 + j\omega M_2 I_2 \tag{2.2}$$

When a metal object is present in the area of the detection coil, it will be affected by the magnetic field and have mutual coupling with transmitting, detection, and receiving coils. This coupling and eddy current in the metal object change induced voltage of the detection coil. New induced voltage is given by [10]:

$$V_d' = j\omega M_1 I_1 + j\omega M_2 I_2 + j\omega M_o I_o \tag{2.3}$$

This variation in induced voltage can indicate the presence of a metal object in the charging area.

2.2 Existing solutions

Two main sensing coil designs have been created to accomplish this. The overlapping sensing coil design consists of two equal loops created from a single wire and designed to overlap as in Fig. 2.1a. Without the presence of a metal object, the magnetic flux through these loops is equal and opposite, causing an overall induced voltage of zero. Upon the disruption of the field by a metal object, the balance of the flux creates an observable voltage. But this pattern calls for a multi-layer structure, which adds to the production complexity and raises costs, and it suffers from blind spots—zones, for instance between the loops, where metal items might not be detected due to flux cancellation.

In contrast, the nonoverlapping sensing coil design uses two adjacent, separate coils, as in Fig. 2.1b. It detects metal objects by measuring the voltage difference between the coils' induced voltages, which remains zero without a metal object but deviates when one coil is affected. This single-layer design is simpler and cheaper to produce, yet it too suffers from blind zones, particularly in the gap between the coils, where a metal object might influence both equally.

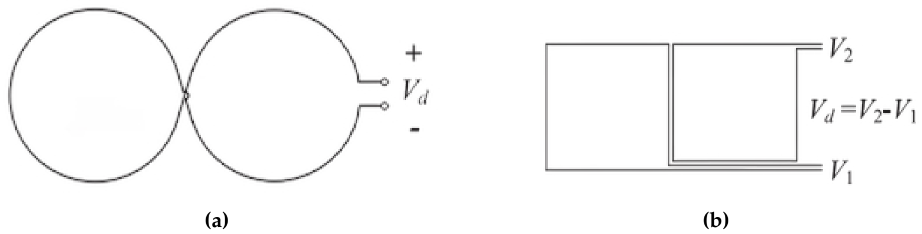


Figure 2.1: Conventional sensing coils (a)Overlapping sensing coils and (b)Non-overlapping sensing coils.

2.3 Proposed sensing coil set

Detection system in this work consists of coil set. Each coil is in rectangular shape and has one turn. Number of coils is even because each two coils form one channel which used to detect any variations in the induced voltage. Coils in each channel must be symmetrical about y axis because magnetic flux generated by transmitting coil is uniform and also symmetric. This can be observed in Fig. 2.2 where results of FEM simulation in Ansys Maxwell 3D is shown. The magnetic field density is symmetric about y and x axis.

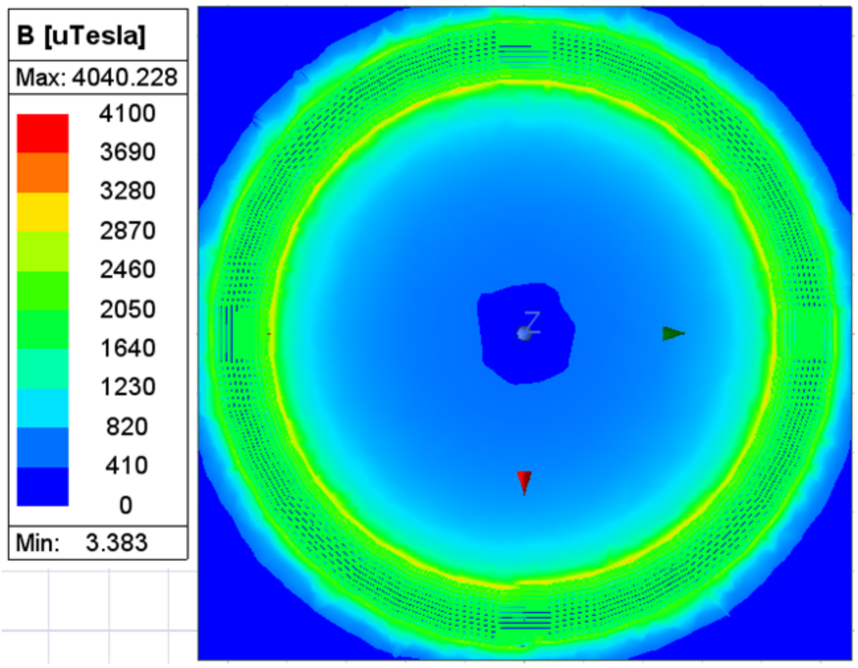


Figure 2.2: Magnetic flux distribution in circular coil

The difference between induced voltages of two symmetric coils can identify whether a metal object is present or not according to equation (2.4):

$$|V_{dn}| = V_{na} - V_{nb} \tag{2.4}$$

where $n = 1, 2, 3, \ldots, k$, is channel number. Any deviation of V_{d0} from zero indicates the presence of a metal object.

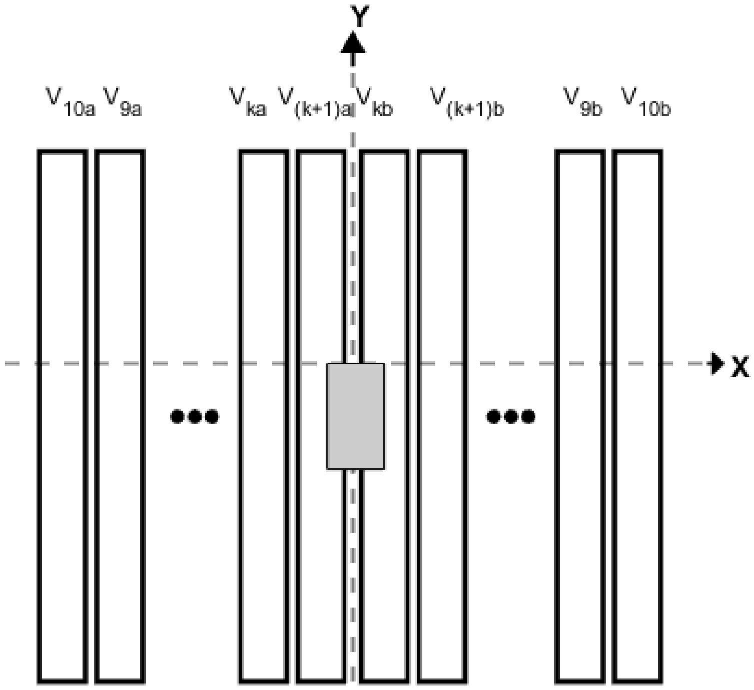


Figure 2.3: Coils arrangement

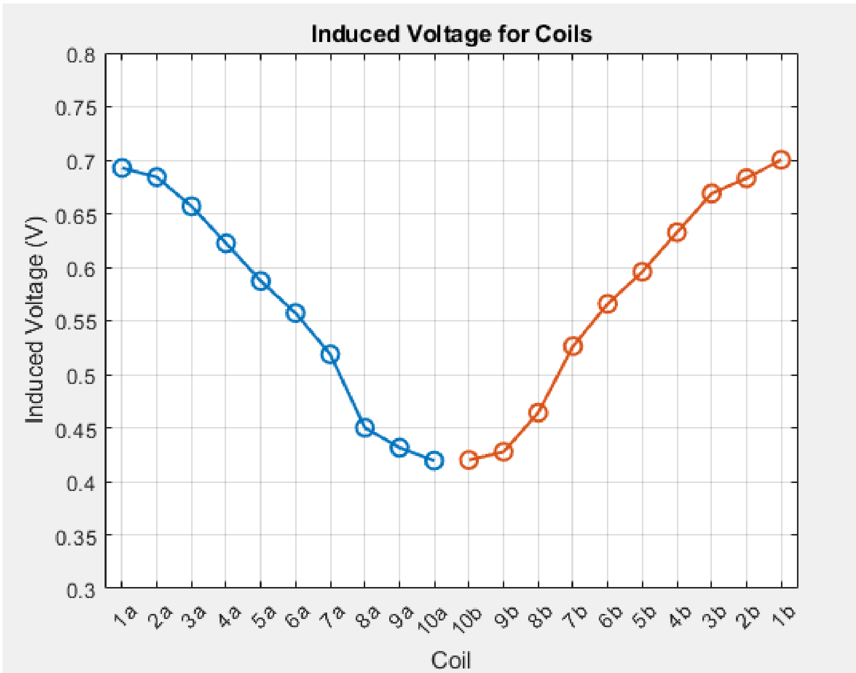


Figure 2.4: Coils arrangement

However, in this design in case of placing metal object right at the center, induced voltages of coils at the center will be the same and metal object cannot be identified. To remove this blind spot, two channels at the center placed asymmetrically as shown in Figure 2.3. In this case, when metal object is right at the center, voltage difference at k channel and k+1 channel will indicate presence of the metal object. From Figure 2.4 it can be seen that channels 1a, 1b, 2a and 2b have very similar induced voltage values. Arranging this two channels asymmetrically will not affect system because voltage difference will be kept at zero.

2.4 Proposed coil design

To cover the whole transmitting coil length of the sensing coils is length of the transmitting coil. The width of the coil is chosen based on the common width of the small metal object which is 40 mm. Metal object also needs to cover at least several coils for better and precise detection. It can be justified by assessing sensitivity of a coil when metal object width is smaller or larger than width of the coil.

If induced voltage of a coil in the absence of any metal object is V_k. Placing metal object will cause change in induced voltage and it will change by ΔV_k. The sensititvity can be written as follows:

$$S = \frac{|V_k - V_k|}{V_k} \times 100 = \frac{\Delta V_k}{V_k} \times 100\ (\%). \tag{2.5}$$

From the fact that magnetic flux density in charging area is uniform, Vk is directly proportional to the area of the detection coil.

$$V_k = \omega B_1 l_c w_c \tag{2.6}$$

In the presence of metal object on the detection coil, there will be eddy current induced and consequently it will induce magnetic flux density Bm. At this point, two cases can be considered. First is when width of MO is larger than width of the coil:

$$V_{k'} = \omega B_1 l_c (w_c - w_m w_c) - \omega B_{\text{ind}} w_m w_c. \tag{2.7}$$

The sensitivity will be

$$S\big|_{w_m > w_c} = \frac{w_m}{l_c}\left(1 + \frac{B_{\text{ind}}}{B_{\text{ext}}}\right). \tag{2.8}$$

From equation above it can be seen that sensitivity of the coil does not depend on width of the coil in this case. Second is when width of MO is smaller than width of the coil:

$$V_{k'} = \omega B_{\text{ext}} (l_c w_c - w_m^2) - \omega B_{\text{ind}} w_m^2. \tag{2.9}$$

Sensitivity:

$$S\Big|_{w_m<w_c} = \frac{w_m^2}{l_c w_c}\left(1 + \frac{B_{\text{ind}}}{B_{\text{ext}}}\right). \tag{2.10}$$

Here sensitivity is inversely proportional to width of the coil. Considering these facts the width of the coil is chosen as 12 mm.

2.5 MOD Circuit Design

To detect variation in induced voltage, metal object detection circuit is proposed, as shown in Fig. 2.5. Circuit consists of the following components: variable resistors, two digital multiplexers, 2nd order active bandpass filter, rectifier, microcontroller unit. Variable resistors will adjust induced voltage of two symmetrical coils to the same level in absence of metal objects as in real life two signals will have difference due to fabrication inaccuracy and environmental factors. After that using controlling signal from MCU, two MUXs will choose needed detection coils. Before processing signal using ADC of MCU, signal needs to go through following stages for better detection: filtering, amplification and rectification. Changes in rectified signals are easier to detect compared to AC signals. Filtering and amplification will be made using the active band pass filter with the gain of 2, 85 kHz center frequency and bandwidth 10 kHz. This will help to filter out noise and distinguish signal. MCU will continuously scan each channel all the time, activating only one of them to not cause coupling between adjacent coils. If there will be any deviations from the induced voltages recorded by MCU at the beginning, system will detect presence of metal object. The flowchart of algorithm for detection of metal object is shown in Fig. .

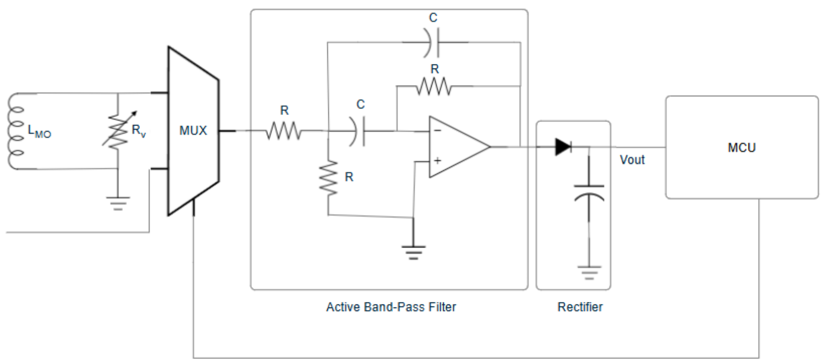


Figure 2.5: MOD Circuit

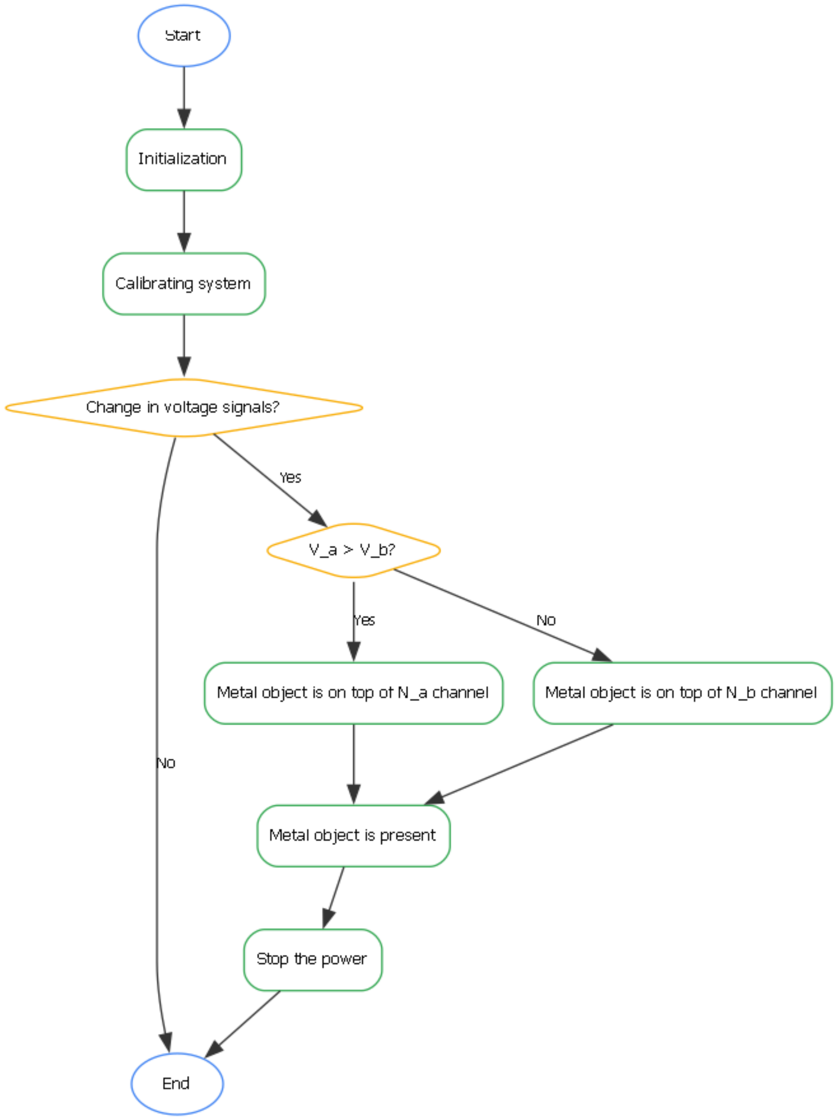


Figure 2.6: System flowchart

Chapter 3

Simulation and Experimental Setup

3.1 System parameters

To make system more close to real case scenario. Parameters for coils such as resonant frequency, number of turns, inner radius, spacing between turns and number of strands were obtained using particle swarm optimization algorithm (PSO). PSO is population based algorithm that was created by observing social behavior of bird flocks. In PSO algorithm swarm of particles iteratively search optimal solution. Each particle is considered as solution, each particle has own search space which consists of specific set of values. Each time they adjust their trajectory and velocity based on the previous positions and neighbors' positions. [15, 21] The algorithm has following components: particles, fitness function, personal best, global best and velocity update rule. Swarm of particles is initialized randomly at the beginning, and in iteration process particles update personal best and global best by choosing the local and global best solutions. PSO algorithm was written in MATLAB. Cost function and constraints are formulated to maximize power efficiency. Parameters range for optimization algorithm are shown in Table 3.1.

Operating Frequency	85 kHz
Input Voltage	24V
Nominal Power	50W
Battery Current	2A
Number of Turns	5 to 50
Inner Diameter	1.25 cm to 25 cm
Resonant Frequency	68 kHz to 85 kHz
Airgap	7 cm
Spacing Between Turns	0.1 mm to 3 mm

Table 3.1: PSO Parameters

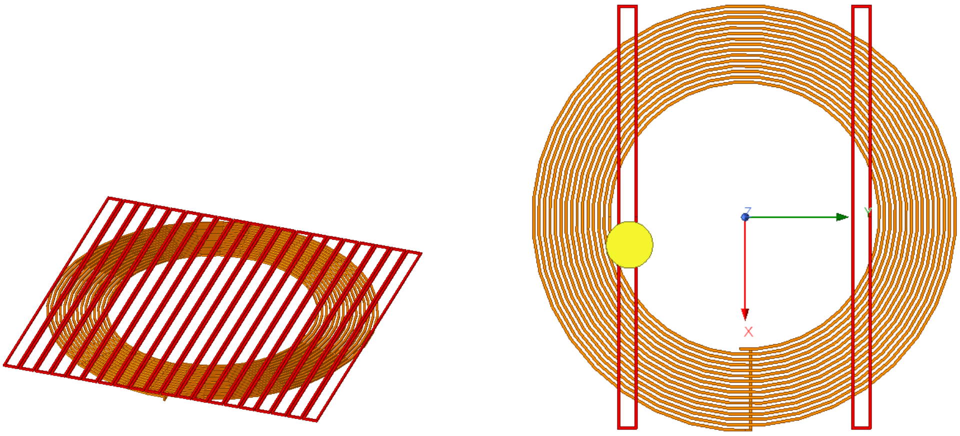
3.2 Simulation

To verify the proposed sensing coil set, simulation model is designed in Ansys Maxwell 3D. Eddy Current solution type is used to perform analysis. The simulation can be seen in Fig. 3.1. The parameters of the system, transmitting and receiving coils are shown in Table 3.2. Simulation setup is shown in Figure . De-

Parameter	**Value**
Frequency	85 kHz
Coil inner radius	85 mm
Coil outer radius	272 mm
Coil turns	15
Air gap	70 mm
Detection coil length	272 mm
Detection coil width	12.65 mm

Table 3.2: Simulation Parameters

tection coil set consist of 20 coils. Knowing that mutual inductance is directly proportional to induced voltage, it is used as indicator of metal object presence in simulation. The mutual inductance values between detection coils and transmitting coil without metal object are shown in graph below. The mutual inductance for each symmetric pairs is the same as seen from the graph. It is clear that in absence of metal object mutual inductance difference is zero. Considering that current is constant, induced voltage difference is also zero. As metal object 15 mm radius copper coin is used. Coin is placed above detection coils at X = -15 mm. Value along Y-axis is changed to test different positions. Channels 1,3,5,7 and 9 are tested.



(a) (b)

Figure 3.1: Simulation setup (a)Coil arrangement and (b)Setup with MO.

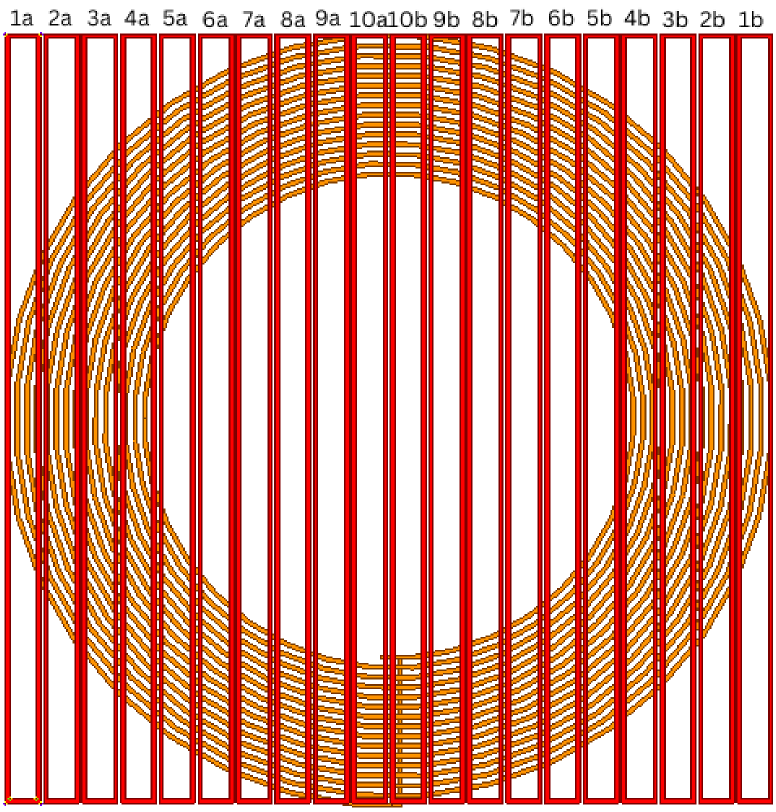
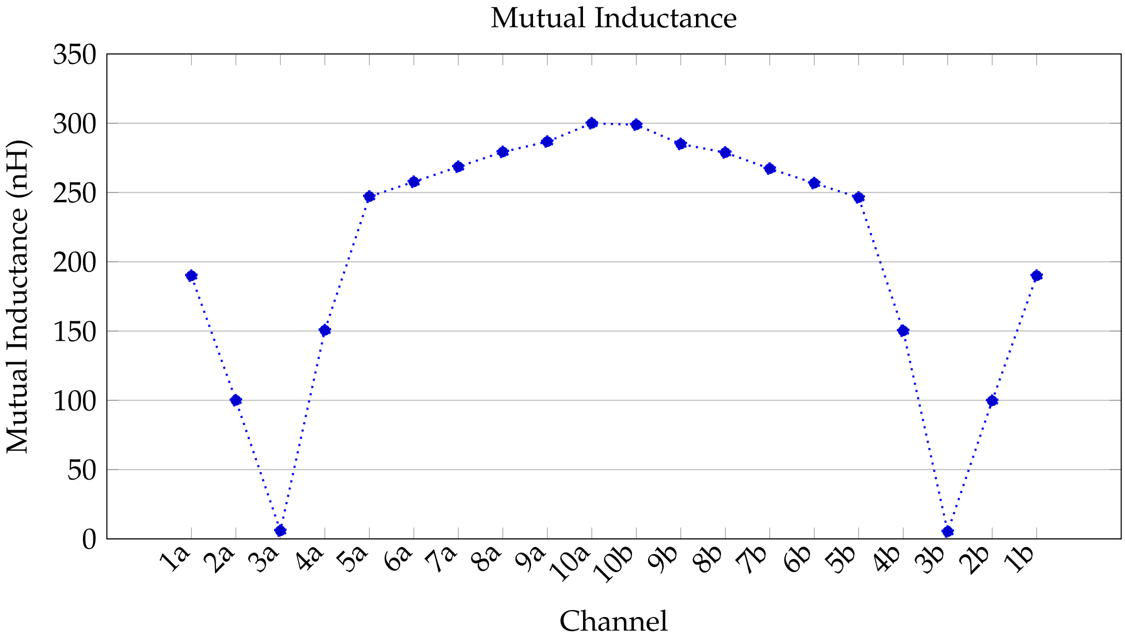


Figure 3.2: Block Diagram


Mutual Inductance
350
300
250
200
150
100
50
0
Mutual Inductance (nH)
1a
2a
3a
4a
5a
6a
7a
8a
9a
10a
10b
9b
8b
7b
6b
5b
4b
3b
2b
1b
Channel

3.3 Experimental setup

To experimentally verify designed system, full setup including H-bridge inverter, full wave rectifier, coils, load and detection coil set are built. Purpose of experimental setup is to test MOD system and see whether it works as intended. H-bridge inverter and rectifier are built on breadboard. For coils litz wire with 160 strands is used. Litz wire width is 0.1 mm. System block diagram and setup are shown in Figure 3.2 and 3.3, respectively.

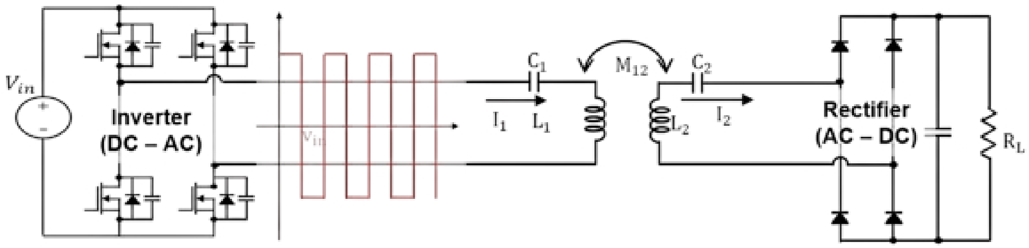


Figure 3.3: Block Diagram

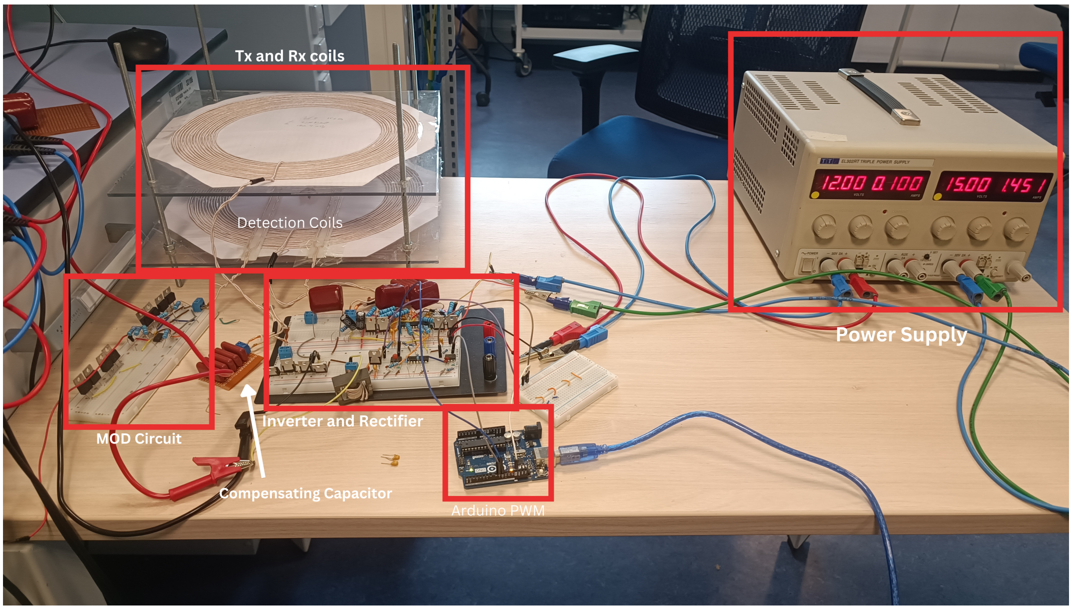


Figure 3.4: Experimental Setup

Chapter 4

Results and Discussion

4.1 Simulation Results

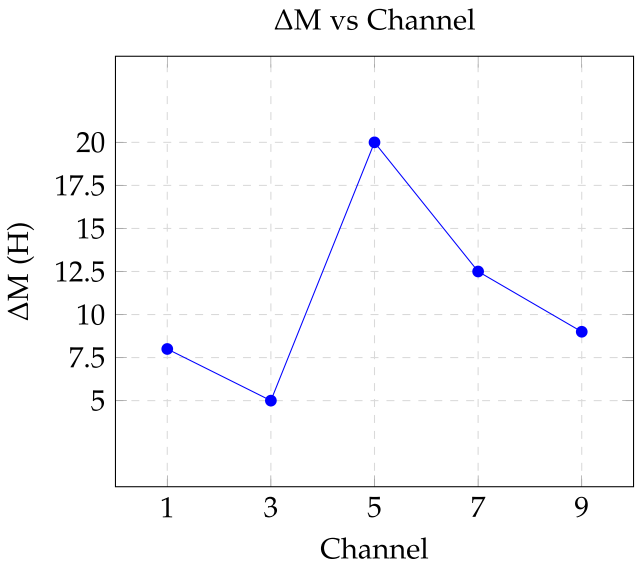


Figure 4.1: Plot of ΔM versus Channel.

The plotted graph, "M vs Channel," is of the measured change in mutual inductance (M) in nanoHenries (nH) for five separate detection channels (Channels 1, 3, 5, 7, and 9) upon the insertion of a metallic object into the charging zone positioned above the detection coil. The figure obviously indicates a considerable difference in M among the examined channels. Channel 5 has the biggest discrepancy in mutual inductance, with a peak of approximately 20 nH, whereas the other channels have much smaller values, with Channel 1 having approximately 8 nH and Channel 3 having the smallest variation of approximately 4 nH. This asymmetrical pattern of

M among the channels is a direct result of the influence of the metal object on the magnetic field, where it causes eddy currents to flow and locally changes the mutual inductance between the sensing and charging coils. The nature and extent of such changes as recorded are empirical verification of the capability of the system to sense the presence of a metallic foreign object and, possibly, deduce its position from the differential inductive response of the array of detection coils.

4.2 Experimental Results

Experimental testing was conducted to evaluate the system response to the presence of a metallic object, in this case an aluminum can shown in Fig. 4.2, placed in the charging area over the detection coil. Can size is 80 mm x 80 mm x 60 mm. Baseline voltage amplitudes were recorded prior to the introduction of the can for two representative channels: Channel 1 measured 864 mV, and Channel 2 measured 688.8 mV. The positioning of the aluminum can caused a noticeable change in the signal amplitudes. The amplitude in Channel 1 fell to 821.3 mV, indicating a decrease in the strength of the detected signal in that channel. Channel 2, on the other hand, showed almost no change in amplitude having 686.8 mV. The difference in the response of the channels highlights the localized nature of the influence of the metallic object on the inductive coupling. The signal amplitude modulation are directly connected with the mutual inductance change occurring between the detection and charging coils, brought about by the eddy currents generated within the conductive aluminum can. The observed reduction in amplitude in Channel 1 and enhancement in Channel 2 are typical of the system's response to the presence of the metal object and show the space-heterogeneous character of its action, and hence the potential for detection and localization of objects. Corresponding signals before MO and after MO are presented in Fig 4.3 and 4.4 respectively.

Figure 4.2: Can for testing

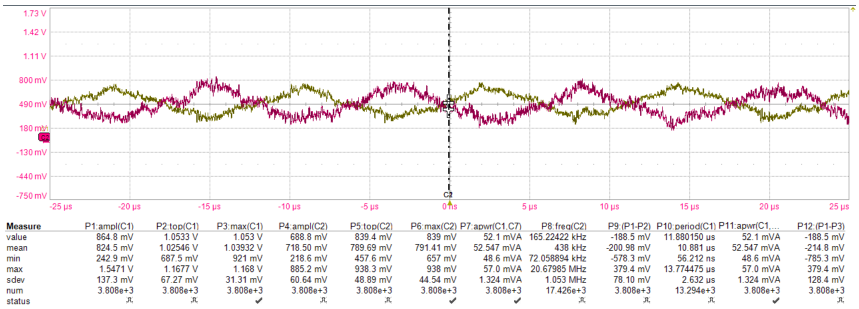


Figure 4.3: Detection signal before MO

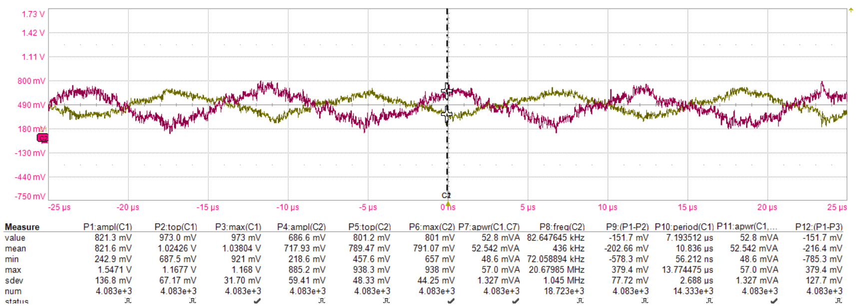


Figure 4.4: Detection signal after MO

Chapter 5

Conclusion

The proposed metal object detection (MOD) system for Wireless Power Transfer (WPT) using the induced voltage method with a symmetrical sensing coil set was studied through simulation and experimental validation. simulations carried out using Ansys Maxwell 3D demonstrated that the existence of a metal object causes significant differences in the mutual inductance among detection coils and the transmitter coil, confirming the principle behind the proposed method. The experiment results, which employed a mockup prototype system and an aluminum can as the foreign object, showed a pronounced difference in the amplitudes of the induced voltage of the detection channels upon the introduction of the object. The change in signal amplitude is directly related to the variation of inductive coupling brought about by the introduction of the metallic object. Both simulation and experimental results empirically confirm the ability of the system devised to detect the presence of metallic foreign objects through measurement of the differential inductive response across the detection coil array, thereby demonstrating its potential for efficient foreign object detection and even localization in inductive power transfer systems.

5.1 Future Work

The successful implementation of the suggested metal object detection (MOD) system for inductive power transfer (IPT) in this study shows the way for different possibilities in future research to improve it. Firstly, the system should be made more sensitive to smaller metal objects, i.e., clips or coins. This could involve the optimization of the geometry of the detection coil by investigating complex designs such as double D and increasing the number of coils to minimize blind zones. The application of machine learning algorithms to the analysis of induced voltage patterns can improve detection accuracy and allow real-time localization of several objects.

Second, the system's effectiveness under dynamic charging conditions must be investigated. MOD system for dynamic IPT will entail coil parameter changes and signal processing in real time to account for varying air gaps and misalignments.

Third, the addition of living object detection (LOD) and is necessary in ensuring safety in public charging environments. This could involve the application of other sensing techniques.

Finally, scalability need to be addressed for industrial adoption. Future research efforts should focus on the simplification of detection coil production using economically cheap materials and standard manufacturing techniques. It will be important to work with industry partners to guarantee the system's accordance to global standards, e.g., SAE J2954.

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