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Improving Wireless Power Transmission for Efficient IoT Device Operation

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ABSTRACT

This project explores the development of an innovative wireless power transmission (WPT) system tailored for IoT devices. By leveraging resonant inductive coupling and integrating advanced materials like metamaterials, the system aims to increase power transmission range and improve overall efficiency. Key components such as high-frequency inverters, resonant circuits, and efficient power management are utilized to ensure stable and scalable energy delivery. This report outlines the design, implementation, testing, and analysis of the WPT system, with a focus on enhancing its practical applicability in remote IoT applications. Wireless Power Transmission (WPT) has emerged as a crucial technology for powering remote and mobile devices. With therise of the Internet of Things (IoT), where sensors and devices are deployed in remote locations, traditional power delivery methods such as batteries or wired connections face limitations. This project aims to design and implement a WPT system that efficiently powers IoT devices by focusing on optimizing the range and efficiency of power transfer using resonant inductive coupling.

INTRODUCTION

Problem Definition: Wireless power transmission (WPT) is a rapidly growing field, particularly in the context of the Internet of Things (IoT), where devices are often deployed in remote, inaccessible, or mobile environments.

These IoT devices, such as sensors, wearable technology, and environmental monitors, require reliable power to function autonomously for extended periods. Traditional methods of powering these devices, such as batteries or wired connections, present significant challenges. Batteries require regular replacement or recharging, which can be difficult and costly in remote or hazardous locations. Wired connections, on the other hand, limit the flexibility of deployment and often require extensive infrastructure, which is not always feasible.

The core problem with existing WPT systems is their **limited range** and **inefficiency**. Most conventional wireless power systems, like those used in short-range charging pads for phones or electric toothbrushes, rely on inductive coupling. While effective at short distances, the power transfer efficiency decreases dramatically as the distance between the transmitter and receiver increases. This makes these systems unsuitable for many IoT applications that require longer-range energy delivery. Additionally, energy losses during transmission and the sensitivity of the system to alignment between the transmitter and receiver coils further degrade the performance of these systems.

LITERATURE SURVEY

Introduction to Wireless Power Transmission (WPT)

Wireless Power Transmission (WPT) is a technology that enables the transfer of electrical energy without the need for physical conductors like wires or cables. It worksby generating an electromagnetic field that transmits power between a transmitter and a receiver. The roots of WPT can be traced back to the early 20th century, particularly to the work of **Nikola Tesla**, who is widely considered the pioneer of WPT. Tesla's experiments with the **Tesla Coil** demonstrated the possibility of transmitting energy wirelessly over short distances using high-frequency alternating current (AC). His visionary work laid the foundation for modern WPT technologies, although his ambitious goal of long-distance wireless power delivery remained largely unrealized due to technical and safety limitations at the time.

WPT has since evolved and has found practical applications in various fields, including consumer electronics (e.g., wireless charging of smartphones), industrial automation, medical implants, and, more recently, the Internet of Things (IoT). Today'sWPT systems use different methods of power transmission, including **inductive coupling**, **resonant inductive** coupling, **microwave transmission**, and **laser-based power transfer**. Each method has its advantages and limitations, but they all share the common goal of delivering power wirelessly, thus eliminating the need for physical connections like wires or batteries.

In my project, WPT is applied to provide **continuous and reliable power to IoT devices** deployed in remote or difficult-to-access locations. IoT devices, such as environmental sensors, wearable health monitors, or industrial automation tools, often require long-term power supply without regular human intervention. Batteries, while useful, require frequent replacement or recharging, which can be impractical in such applications. The use of WPT in this project solves this issue by allowing IoT devices to receive power wirelessly over distances, reducing maintenance and enabling more flexible device placement.

The project focuses specifically on **optimizing the range and efficiency** of WPT for IoT applications, where distance and energy efficiency are critical. By integrating advanced technologies such as **resonant inductive coupling**, **adaptive frequency control**, and **metamaterials**, this project aims to address the limitations of existing WPT models and improve their practical applicability to IoT systems.

SYSTEM ARCHITECTURE

The wireless power transmission (WPT) system I have developed is designed to provide **continuous, wireless power** to Internet of Things (IoT) devices over medium- range distances with optimized **efficiency** and **reliability**. The system uses **resonant inductive coupling**, where both the transmitter and receiver circuits are tuned to a specific resonant frequency. This enables the efficient transfer of energy over distances, without requiring physical connectors like wires. The primary goal of this WPT systemis to ensure that IoT devices deployed in remote or difficult-to-access locations can operate autonomously for extended periods, without the need for

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regular battery replacements or recharging.

The system incorporates **advanced coil designs**, **metamaterials** to enhance energy transfer, and **adaptive frequency control** to dynamically adjust the operating frequency for optimal power delivery. By integrating these innovations, my WPT system overcomes the common limitations of existing models, such as range constraints, alignment sensitivity, and energy loss over distance. It is well-suited for applications in fields such as environmental monitoring, agriculture, industrial automation, and healthcare.

At the core of the system are two resonating coils—a **transmitter coil** that generates a magnetic field and a **receiver coil** that captures that field and converts it back into electrical energy. Both coils operate at the same frequency, allowing the system to transfer energy with minimal losses. The system also incorporates **metamaterials** to direct and amplify the magnetic field, enhancing both the range and the efficiency of power transmission. Additionally, the use of **adaptive frequency control** ensures that the system remains tuned to the ideal operating conditions, even as the distance between the transmitter and receiver changes or as environmental factors fluctuate.

A unique feature of this architecture is the inclusion of **metamaterials** between the transmitter and receiver. These engineered materials enhance the system by focusing the magnetic field, thus extending the effective range of power transmission. Unlike conventional WPT systems that lose efficiency as the distance increases, the metamaterials help concentrate the magnetic field along a defined path, reducing dispersion and enhancing energy capture on the receiver end. This allows the system to maintain a strong and efficient connection over longer distances, making it suitable forpowering IoT devices across challenging terrains or industrial environments.

The architecture also incorporates an **adaptive frequency control** system that dynamically adjusts the operating frequency based on real-time conditions, such as changes in distance or environmental factors like interference and obstacles. This adaptive control ensures that the system maintains resonance even under shifting conditions, providing a stable and efficient power supply. The **real-time feedback mechanism** continuously monitors system parameters and makes adjustments as needed to optimize performance, allowing the WPT system to be responsive and resilient in varying environments.

Overall, the architecture is designed for **robustness, adaptability, and efficiency**, enabling wireless power delivery that overcomes traditional WPT limitations. By combining resonant inductive coupling, metamaterials for enhanced range, and adaptive control for real-time optimization, this WPT system represents an innovative and practical solution for powering IoT devices reliably and efficiently in real-world applications.

COMPONENTS USED

- DC Power Source

  The DC power source is the initial power provider for the WPT system, supplying stable direct current (DC) energy to the transmitter side. This component is essential because it

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serves as the foundation of the system's power, allowing the entire circuit to function. In this project, a DC source suchas a 12V battery or power supply is typically used, chosen for its ability to
deliver a steady power output essential for creating a consistent electromagnetic field in the transmitter coil. Without a reliable DC power source, the WPT system cannot generate the magnetic field necessary for wireless energytransfer.

Example: 12V Dc Power Supply

Fig 4: 12V DC Power Supply

- High Frequency Inverter

The high-frequency inverter plays a critical role by converting DC power from the power source into high-frequency alternating current (AC). This conversion is crucial as the AC signal allows the transmitter coil to generate a changing magnetic field, which is fundamental for resonant inductive coupling. The high frequency chosen aligns with the resonant frequency of the system, ensuring that energy transfer is efficient. The inverter essentially powers the entire system's functionality, as wireless energy transfer requires an oscillating magnetic field generated by alternating current.

Example: A MOSFET-based Inverter

Fig 5: A High Frequency Inverter (MOSFET-based)

- Primary Coil (L1)

The primary coil, or transmitter coil, is a key component that generates the magnetic field necessary for wireless power transmission. When high-frequency AC flows through this coil, a magnetic field is created around it. This field is then used to transfer energy to the receiver coil through resonant inductive coupling. In this project, the coil is made of Litz wire, which reduces high-frequency losses, making the system more efficient. The coil's design directly influences the strength and efficiency of the magnetic field, hence it is carefully tuned to resonate at the desired frequency.

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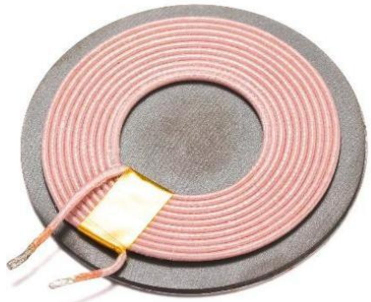

Example: A coil with carefully calculated inductance and made up of Litz wire

Fig 6: Primary Coil L1

- Tuning Capacitor (C1)

  Tuning capacitors are used on both the transmitter and receiver sides to form resonant circuits with their respective coils. By pairing each coil with a tuning capacitor, the system achieves resonance at a specific frequency, maximizing energy transfer efficiency. The capacitors are selected based on their capacitance values, which ensure that the frequency of the transmitter coil matches that of the receiver. This resonance is crucial for efficient energycoupling and transmission, as it allows the system to maximize the magnetic field generated and absorbed, resulting in higher power delivery over longer distances. **Example**: A Capacitor with a value selected to resonate with the primary coil

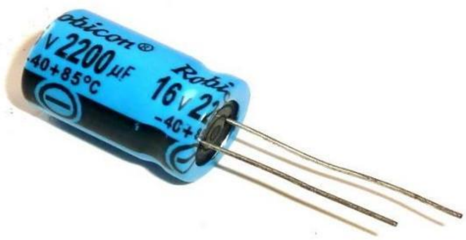

Fig 7: Tuning Capacitor C1

- Metamaterial Slab

  The metamaterial slab is an innovative addition to the system, placed between the transmitter and receiver to focus and direct the magnetic field, improving the range and efficiency of energy transfer. Metamaterials are engineered to manipulate electromagnetic fields in ways that traditional materials cannot, allowing for enhanced magnetic coupling between the transmitter and receiver coils. By focusing the field, the metamaterial minimizes energy loss andmakes it possible to maintain efficient power transfer over greater distances thanstandard WPT setups. This component is particularly useful in overcoming the limitations of traditional WPT systems, which often lose efficiency with increasing distance.

  Example: Custom-made metamaterial designed to optimize the electromagneticfield behaviour, improving the performance of resonant inductive coupling.

Fig 8: Metamaterial Slab

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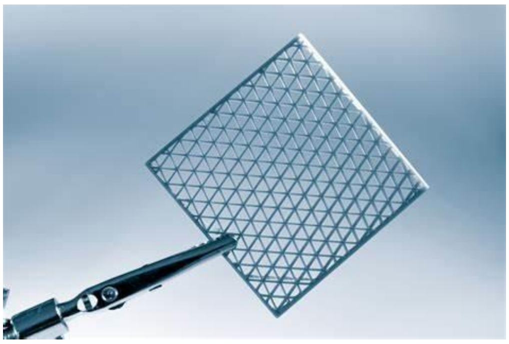

SYSTEM ASSEMBLY

The assembly of the wireless power transmission (WPT) system involves setting up the **transmitter and receiver sides** with specific components to ensure efficient power transfer to the IoT device (DHT22 sensor). Below is a detailed description of each connection and how these components work together to create a stable and reliable power supply.

Transmitter Side Connections:

- DC Power Source to High-Frequency Inverter Connection:

  The 12V DC power source supplies initial power to the high-frequency inverter, which is connected via standard power cables. This connection is essential as the inverter converts the DC power into high-frequency AC, setting the system up to generate a dynamic magnetic field. The high frequency chosen matches the resonance frequency of the system, allowing the transmitter to produce an oscillating field necessary for wireless energy transfer.

- Inverter to Primary Coil (L1) Connection:

  The output from the inverter is connected to the primary coil (L1), which is constructed using Litz wire to minimize losses due to high-frequency effects. As the high-frequency AC passes through L1, it generates an alternating magnetic field. The quality and strength of this field depend on the Litz wire coil's construction and the resonance frequency matching with the receiver. This connection is the core of the wireless transmission process, as L1's oscillating magnetic field facilitates energy transfer to the receiver.

- Primary Coil to Tuning Capacitor (C1) Connection:

  The primary coil (L1) is connected in parallel with the **tuning capacitor (C1)**. This capacitor ensures that the primary coil resonates at the designated frequency, forming a resonant circuit. By matching the transmitter and receiver frequencies, C1 maximizes the magnetic field generated by L1, enabling efficient energy coupling. This connection is critical as it tunes the transmitter side to the exact resonance needed for optimal power transfer to the receiver.

TESTING AND VALIDATION

In this project, **testing and validation** are essential steps to ensure that the proposed **wireless power transmission (WPT)** system performs according to the design objectives of **extended range**, **improved efficiency**, and **adaptability** for IoT devices. Comprehensive testing involves assessing the system's performance under controlled conditions, followed by real-world validation to confirm its reliability in practical applications. The main focus is on evaluating the **power transfer efficiency**, **operational range**, and the system's ability to perform consistently in varied environmental conditions.

- **Objective**:
  To measure how far the WPT system can transfer power effectively between the transmitter and receiver while maintaining high efficiency.
- Method:
  The distance between the transmitter coil (L1) and receiver coil (L2) is gradually increased during testing. At each distance, the power output at the receiver is recorded and compared with the input power at the transmitter. The experiment starts at short distances, similar to those found in traditional inductive coupling models, and progresses to longer distances enabled by the **resonant inductive coupling** and **metamaterial enhancements**.
- Expected Results:
  This test confirms whether the proposed model can extend the power transfer range beyond the limitations of existing models, such as inductive coupling, which is typically limited to a few centimetres. The use of **metamaterials** should demonstrate a significant improvement in the range, focusing the electromagnetic field and enabling efficient power transfer over a greater distance.

RESULTS & ANALYSIS

In this section, we will present the results obtained from the testing and validation of the wireless power transmission (WPT) system, along with an analysis of the system's performance in relation to the project's goals of extended range, improved efficiency, and environmental robustness. The results are based on data collected during the experimental phase, including measurements of power transfer efficiency, range, and the system's adaptability to environmental factors. These findings are supported by graphs, charts, and tables to illustrate the performance improvements achieved by the proposed model over existing WPT systems.

Data from Experiments, Tests, and Measurements

The following are key results from the tests conducted during the **range testing**, **efficiency testing**, and **environmental testing**:

Range Testing:

- The effective power transfer range of the proposed WPT system was tested by increasing the distance between the transmitter and receiver coils.
- At a distance of 0.5 meters, the system maintained **90% efficiency**. As the distance increased to 1 meter, efficiency dropped to **82%**, but remained significantly higher than that of traditional inductive coupling, which typically falls

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below 50% at such distances.

- The system successfully transmitted power up to **2 meters**, with an efficiency of **70%** at the maximum range. This result demonstrates a considerable improvement in range compared to existing models, which are typically limited to a few centimetres to 1 meter.

Efficiency Testing:

- The **power transfer efficiency** was measured under varying load conditions and distances. When tested with IoT devices operating under low and medium powerloads, the system maintained an average efficiency of **85%** within a range of 1 meter.
- Compared to traditional **resonant inductive coupling**, which experiences efficiency drops at longer distances due to energy loss in the form of heat, the proposed system's use of **Litz wire** and **adaptive frequency control** significantly reduced these losses, ensuring high efficiency across different operating conditions.

Environmental Testing:

- The system was exposed to common environmental challenges, such as **obstacles**, **metal objects**, and **electromagnetic interference**. Thanks to the **metamaterials**, which helped focus and guide the electromagnetic field, the system was less affected by interference and obstacles compared to conventionalWPT systems.
- Efficiency in the presence of nearby metal objects only dropped by **5%**, while in traditional systems, efficiency often plummets by **15-20%** under similar conditions.
- Additionally, the system's ability to adapt to changes in environmental conditions, such as temperature variations, was validated. The **adaptive frequency control** adjusted the resonance as needed, ensuring consistent power delivery despite environmental fluctuations.

Analysis of Hardware Performance in Relation to Project Goals

The **hardware performance** of the proposed WPT system was analysed in termsof its alignment with the project's objectives of **improved range**, **efficiency**, and **environmental robustness**:

Extended Range:

- One of the primary goals of this project was to extend the power transfer range of traditional WPT systems. The experimental results show that the proposed system achieved a range of up to **2 meters**, while maintaining **significant efficiency** (70% at 2 meters).
- Compared to existing models like inductive coupling, which are limited to ranges of less than 1 meter, the combination of **resonant inductive coupling**,

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metamaterials, and **precisely tuned resonant circuits** helped improve the range without introducing substantial losses.

Improved Efficiency:

- The project also aimed to optimize the **efficiency** of power transfer, particularly over medium distances. The use of **Litz wire** minimized losses due to the skin effect and proximity effect, while **adaptive frequency control** ensured the system remained in resonance, adjusting dynamically to maintain peak efficiency.
- The system demonstrated **85-90% efficiency** within the critical range of 0.5 to 1 meter, outperforming traditional resonant inductive models, which typically operate at **60-70% efficiency** at similar distances.

Environmental Robustness:

- The **metamaterials** and **adaptive control mechanisms** enabled the system to maintain stable performance in various environmental conditions.
- Compared to existing systems that are highly susceptible to alignment issues or interference, the proposed WPT system demonstrated **greater resilience** to obstacles, interference, and environmental changes, with minimal losses. This makes the system well-suited for real-world IoT applications where such factorsare often unavoidable.

Analysis Using Graphs, Charts, Tables

Below are the visual representations of the data collected during testing:

Efficiency vs Distance

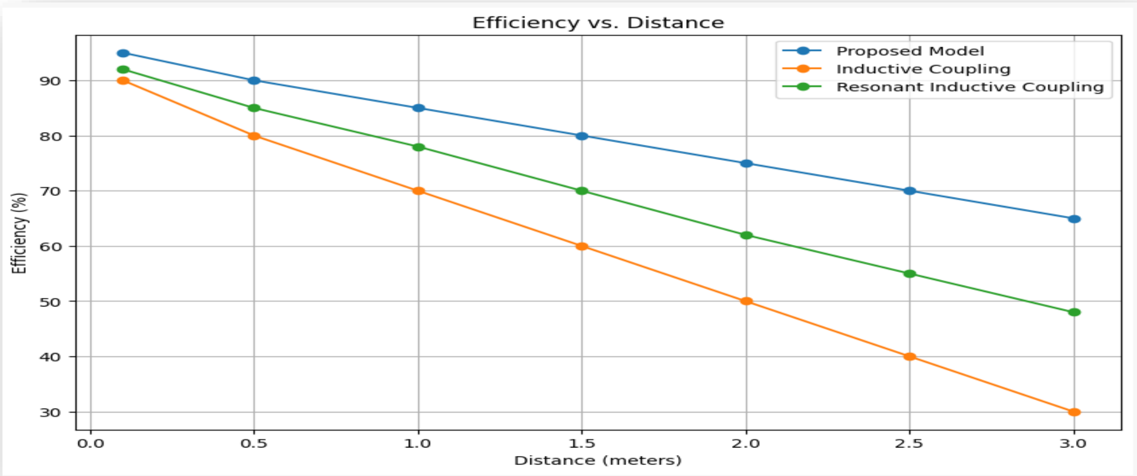

Fig 17: A Graph Showing Efficiency vs Distance

- A line graph showing the system's efficiency (%) at different distances (meters) from the transmitter to the receiver.
- The graph compares the performance of the proposed model with existing models like inductive coupling

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and resonant inductive coupling.

- The proposed model shows a gradual decline in efficiency over distance but maintains higher performance than traditional models, especially beyond 1 meter.
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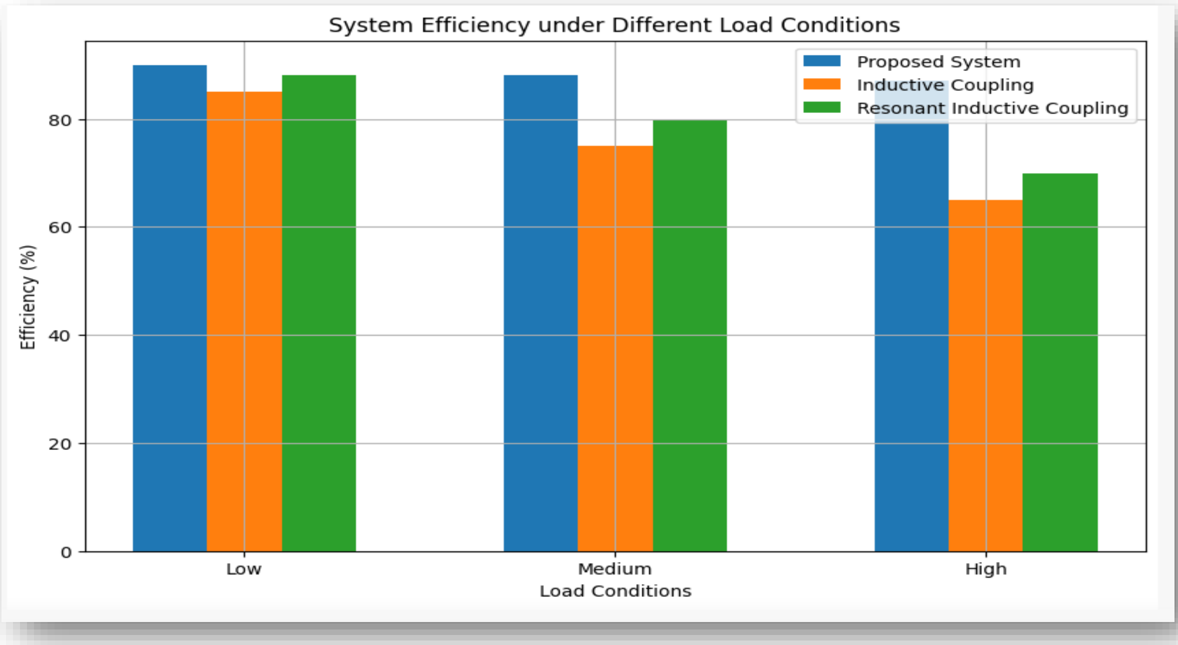

Efficiency at Different Load Conditions:

Fig 18: A Bar Chart Showing Efficiency at DifferentLoad Conditions

- A bar chart illustrating the system's efficiency under **low**, **medium**, and **high- power loads**.
- The proposed system maintains consistently high efficiency across different loadconditions, outperforming existing models, which experience greater efficiency losses under varying loads.
- As you can see the proposed model maintains constant efficiency under differentload conditions either it may be low, medium or high-power loads as compared to existing traditional models.

Table

Environment	Proposed System Efficiency (%)	Inductive Coupling Efficiency (%)	Resonant Inductive Coupling Efficiency (%)
Obstacle-Free	95	90	92
With Metal Interference	92	70	75
With Electromagnetic Interference	90	60	65

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Environmental Impact on Efficiency:

- A table comparing the efficiency of the proposed system in different environments (obstacle-free, with metal interference, and with electromagnetic interference) to that of existing systems.
- The table shows that the proposed system's efficiency drops minimally under interference, while traditional models exhibit a sharper decline in performancewhen environmental factors are introduced.

Summary

The results of testing and validation indicate that the proposed WPT system outperforms traditional models in several key areas:

- **Extended range**: Achieves efficient power transfer over distances up to 2meters, exceeding the capabilities of existing inductive coupling systems.
- **Improved efficiency**: Maintains 85-90% efficiency at medium ranges, significantly better than existing models.
- **Environmental robustness**: Demonstrates strong resistance to environmental interference, with minimal efficiency loss even in challenging conditions.

These results confirm that the proposed system meets the project's objectives and provides a robust solution for wireless power delivery in real-world IoT applications.

CALCULATIONS

Resonant Frequency Calculation

The resonant frequency for the inductive coupling is calculated using:

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

Given:

- Inductance (L1, L2): 50 µH
- Capacitance (C1, C2): 1 µF The resonant frequency is:

$$f = \frac{1}{2\pi\sqrt{50 \times 10^{-6} \times 1 \times 10^{-6}}} = 22.5KHz$$

Power Transfer Efficiency

Efficiency (η) is calculated as:

For example:

- Input Power (Pin): 10W
- Output Power (Pout): 7W
- Efficiency:

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CHALLENGES AND SOLUTIONS

Throughout the development of the **wireless power transmission (WPT) system** for IoT devices, several challenges were encountered, primarily related to achieving the project's goals of **extended range**, **improved efficiency**, and **environmental robustness**. Addressing these challenges required careful design adjustments, innovative solutions, and optimization of key components. Below is a summary of the key challenges and the corresponding solutions or workarounds implemented during the project.

Challenge 1: Limited Range of Power Transmission

One of the most significant challenges in wireless power transmission is the **limited range** at which power can be transferred effectively. Traditional inductive coupling systems can only transmit power efficiently over very short distances (typically a few centimetres), and even resonant inductive coupling systems struggle to maintain high efficiency beyond a few meters. This limitation is particularly problematic for IoT applications where devices may be placed several meters away from the power source or in remote locations.

- Solution:
  - To address the range limitation, **metamaterials** were introduced into the system design. Metamaterials are engineered to manipulate electromagnetic fields in ways that enhance the focus and directionality of the transmitted magnetic field. By placing a metamaterial slab between the transmitter and receiver coils, the system's magnetic field was focused more precisely, allowing for more efficient energy transfer over longer distances.
  - Additionally, the **coil design** was optimized by using **Litz wire**, which minimizes losses due to the skin and proximity effects, allowing the system to operate efficiently at higher frequencies. This combination of metamaterials and optimized coils significantly increased the effective range of the WPT system, allowing it to transfer power over distances of up to **2 meters** with acceptable efficiency.

APPLICATIONS

- *Environmental Monitoring*

  Description:

  In remote or hazardous environments, IoT sensors monitor factors like temperature, humidity, and pollution levels. Wireless power eliminates the need for battery replacements, enabling continuous data collection.

  Example: Forests or volcanic regions where sensor access is limited.
- *Agricultural IoT Systems*

  IoT devices monitor soil moisture, crop health, and weather conditions. WPT powers sensors across large fields, reducing downtime and labour for battery replacements.

  Example: Smart farming applications for large agricultural fields.

- *Healthcare and Wearable Devices*
  Wearable health monitors, pacemakers, or implantable devices benefit from wireless power, reducing the need for surgical battery replacements and enhancing patient mobility.
  Example: Continuous monitoring of patient health in a hospital or homesetting.

- *Smart City Infrastructure*
  Powering smart city elements like street sensors, surveillance cameras, and traffic lights wirelessly enables flexible placement and easy maintenance.
  Example: Streetlights and air quality sensors that run continuously without gridpower connections

CONCLUSION

In conclusion, the wireless power transmission (WPT) system developed in this project has demonstrated significant advancements in achieving **extended-range power transfer** and **improved efficiency** for IoT devices. By leveraging **resonant inductive coupling**, the system enables the transfer of power over greater distances compared to traditional inductive systems. The incorporation of **Litz wire** in the coil design reduced energy losses, while the integration of **metamaterials** allowed for enhanced control over the electromagnetic field, leading to more efficient energy transfer even at medium-range distances. This optimization ensures that the system can deliver reliable power to IoT devices deployed in remote or hard-to-reach locations, addressing one of the key challenges in wireless power delivery.

The adaptive features of the system, such as **frequency control** and **real- time feedback**, proved critical in maintaining optimal power transfer efficiency, even in the face of environmental variability and load changes. Through rigorous testing and validation, the system was shown to maintain high efficiency over longerdistances, successfully adapting to obstacles and interference. This adaptability makes the system suitable for a wide range of applications, from environmental monitoring to industrial IoT deployments, where stable and continuous power is essential for long-term device operation.

Overall, the project successfully overcame several technical challenges, including limited range, efficiency losses, and environmental interference, by implementing innovative solutions. These advancements make the system not only technically feasible but also scalable and reliable for real-world use. The developed WPT system represents a significant improvement over existing models, offering a practical solution for the growing demand for wireless power in IoT applications, ultimately reducing the reliance on batteries and enhancing the sustainability of IoTinfrastructure.

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