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Analysis Of Wireless Energy Transfer Systems By Methods Inductive Resonance

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ABSTRACT
This research investigates wireless energy transfer techniques using the inductive resonance method. This method utilizes resonance between the sending and receiving coils to increase energy transfer efficiency. The main focus is the analysis of resonance characteristics that affect energy transfer efficiency, such as resonance frequency, coil quality, and distance between transmitter and receiver. This research uses an analytical approach to measure key parameters such as voltage and current on both sides of the transfer. The collected data is analyzed to understand the relationship between resonance parameters and overall system efficiency. The analysis results will be used to validate the mathematical model developed to optimize the system design. This research is expected to provide valuable insights to increase efficiency and transfer distance in the application of inductive resonance-based wireless energy transfer technology.

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INTRODUCTION

Wireless energy transfer (WET) has become an exciting area of research in recent years due to its potential to revolutionize various industries. WET can be used to wirelessly transfer energy to electronic devices without the need for wires or physical contact. This could be useful for a variety of applications, such as charging portable electronic devices, medical implants, and electric vehicles.

One of the most promising WET methods is resonance energy transfer (RET). RET utilizes the phenomenon of magnetic resonance to transfer energy between two adjacent coils. This method offers several advantages over other WET methods, such as high efficiency, long transfer distance, and the ability to transfer energy through non-conductive media.

Research on designing WET systems using the resonance method is still developing. One of the main challenges in designing RET systems is achieving high energy transfer efficiency. Energy transfer efficiency refers to the percentage of energy transferred from the transmitter coil to the receiver coil. The background to designing a wireless energy transfer system using the resonance method involves two main elements: the basic concept of resonance and its application in wireless energy transfer.

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The aim of research on wireless energy transfer systems using the resonance method is to develop an efficient and effective system for transferring electrical energy without cables and also increasing the efficiency of energy transfer between the energy source and the receiving device. This can be achieved by optimizing the resonant coil design, operating frequency and other parameters. The same thing can also reduce environmental influences, where wireless energy transfer systems are susceptible to electromagnetic interference and long distances between coils. The main challenge faced by WET is the limited transfer distance. This research will also increase the transfer distance without sacrificing efficiency. By achieving these goals, this research is expected to make a significant contribution to the development of better wireless energy transfer technology and wider application in various fields.

Literature Review

Electromagnetic Fields

An electromagnetic field is a physical field generated by changing electric charges and magnetic fields. This phenomenon is based on the electromagnetic theory proposed by James Clerk Maxwell in the 19th century. This theory explains that electric fields and magnetic fields are interrelated and can propagate in the form of electromagnetic waves. This field cannot be seen directly, but its effects can be observed through various physical phenomena, such as Lorentz force, electromagnetic induction, and electromagnetic waves.

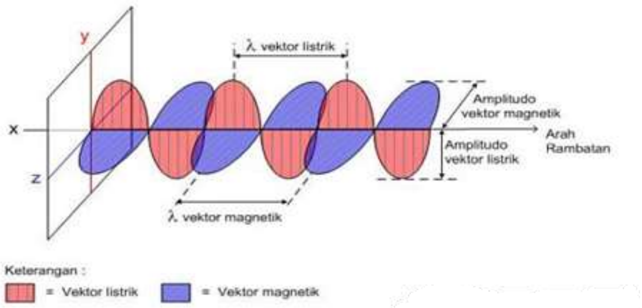

Figure 1. Electromagnetic Waves

Electromagnetic waves are composed of propagating electric fields E and magnetic fields B which are perpendicular to each other. According to Maxwell, the speed of propagation of electromagnetic waves depends on the magnetism and electricity of the medium or does not depend on the amplitude of the field vibrations.

Inductance

Inductance is the property of a wire or electric circuit that determines how large a magnetic field is produced by an electric current flowing through it. Quantitatively, inductance is defined as the ratio between the total magnetic flux produced by an electric current to the magnitude of that current. Inductance is generally measured in henry units (H).

For a solenoid with winding length l, number of turns N, and cross-sectional area A, the inductance L can be calculated using the equation:

$$L = \frac{\mu_0 \mu_r N^2 A}{l}$$

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Where:
μ0 is the vacuum permeability (a constant whose value is 4π×10−74 H/m),
μr is the relative permeability of the medium around the solenoid,
N is the number of turns,
A is the cross-sectional area of the solenoid, and
l is the length of the solenoid.

Self Inductance

Inductance is a property of an electrical circuit or electronic device that determines how large a magnetic field is produced when an electric current flows through it. Conceptually, inductance is a measure of the ability of a component to generate magnetic flux in response to current flowing through it. Mathematically, inductance L is measured in henry units (H) and is defined as the ratio between the magnetic flux Φ produced by current I to the magnitude of that current:

$$L=,\varphi\text{-}I.$$

Where:
L is the inductance (in henries),
Φ is the magnetic flux (in weber, Wb), and
I is the flowing electric current (in amperes, A).

Inductance depends on several factors, including the number of turns of wire (for inductors such as solenoids or toroids), the geometry of the device (such as the shape and size of the solenoid or toroid), and the nature of the insulating material around the windings (taking into account the permeability of the medium).

Mutual Inductance

Mutual inductance(mutual inductance) is a phenomenon in which changes in electric current in one coil cause changes in electric current in another nearby coil. When an electric current flows through a coil (coil 1), the resulting magnetic field can cut another coil (coil 2) that is nearby. This change in the magnetic field in coil 2 produces an induced electromotive force (EMF), in accordance with Faraday's law.

The mutually induced voltage is defined as when current (i) flows through the coil, then around the coil a magnetic flux (φ) will arise. Based on Faraday's law, a coil that experiences a changing magnetic field will produce an induced voltage of V which is proportional to the multiplication of the number of turns N and the change in flux (φ) per time. In electrical circuits, inductance is often described as an inductor component that has the ability to store energy in the form of a magnetic field. When an electric current passes through an inductor, a magnetic field forms around it. When the current changes, the magnetic field also changes, inducing an inductance emf that opposes the change in current.

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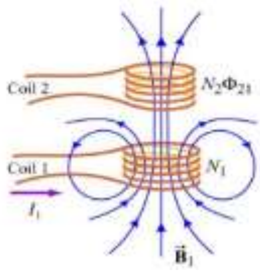

Figure 2. Mutual Inductance M21 on the Coil N2 Caused by Coil N1

Mutual inductance (symbol: M) consists of two inductors that induce each other with the equation:

M21= N1.N2.P21

M21= M12

Where :

M21 = Mutual inductance value which shows the connection of the induced EMF in coil 2 caused by changes in current in coil 1

N1 = Number of turns in coil 1

N2 = Number of turns in coil 2

P21 = Permeance of the space where the magnetic flux is located

Linkage indicator between coupled coils expressed as a coupling coefficient. Coefficient coupling is valued between 1 and 0, and is expressed as an equation:

M=k,-,L-1.,L-2..

Where :

k = Coupling coefficient ($0 \leq k \leq 1$)

L1 = Inductance value of the first coil

L2 = Inductance value of the second coil

Factors Affecting Mutual Inductance

1. Number of Windings: The more turns in the coil, the greater the mutual inductance.
2. Distance Between Coils: The closer the distance between two coils, the greater the mutual inductance.
3. Magnetic Field Density: A stronger magnetic field will produce a greater induction.
4. Core Ingredients: Using core materials with high magnetic permeability (such as iron) will increase mutual inductance.

If both sides of the coil are an LC circuit where the voltage frequency becomes important. The mutual inductance value between the two coils determines the shape of the frequency response curve. The frequency response curve consists of loose-coupling, critical-coupling, and over-coupling. If the frequency response curve of the coil circuit is loose-coupling, then the bandwidth size will be narrow. When the mutual inductance value is increased, the bandwidth size of the frequency response curve also increases. However, when the mutual inductance value exceeds the critical point, the bandwidth response will begin to decrease.

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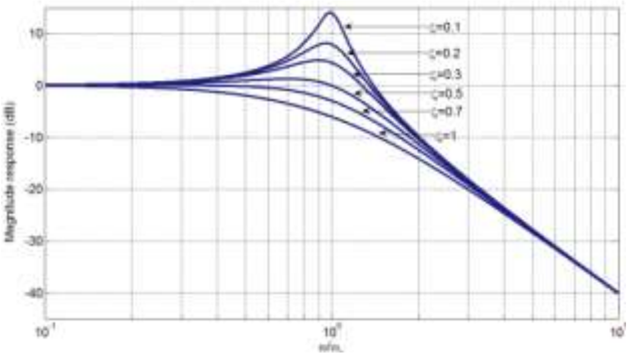

Figure 3. Loose-coupling, critical-coupling and over-coupling frequency response curves.

Wireless Energy Transfer Research

Wireless Energy Transfer (WET) or wireless energy transfer has become an interesting area of research over the last few decades. This technology allows the transfer of energy between two devices without the need for cables or physical contact. WET has many potential applications, such as charging portable electronic devices, medical implants and electric vehicles. The following is some previous research that has been carried out in this field:

1. Kurs, A., et al. (2007). This research is one of the first to introduce the concept of wireless energy transfer via magnetic resonance. This research shows that energy transfer can be carried out efficiently over relatively long distances using the principle of magnetic resonance.
2. Sample, A.P., et al. (2011). This research analyzes a wireless energy transfer system with magnetic resonance theoretically and experimentally. This research also discusses distance adaptation techniques to increase energy transfer efficiency over varying distances.
3. Cannon, B.L., et al. (2009). This research explores the possibility of wireless energy transfer to several small receivers simultaneously using the principle of magnetic resonance. This research shows that energy transfer to several receivers simultaneously can be carried out with good efficiency.
4. Ahn, D., & Hong, S. (2014). This book discusses the basic principles of wireless energy transfer by magnetic resonance, including theory, resonator design, analysis, and practical applications.
5. Xie, L., et al. (2013). This article discusses the application of wireless energy transfer technology in wireless sensor networks, including existing challenges and solutions.
6. Pantic, Z., & Bhuiyan, S. M. (2015). In Wireless Power Transfer for IoT and Wearables (pp. 1-22). CRC Press.

This book discusses the application of wireless energy transfer in Internet of Things (IoT) and wearable devices, as well as the components needed for its implementation. These studies have made significant contributions to the development of wireless energy transfer technology, especially the magnetic resonance method. Nevertheless, there are still challenges and opportunities for further research to improve the efficiency, transfer distance, and wider application of this technology.

Wireless Energy Transfer (WET) or wireless energy transfer is a method for transferring electrical energy from one point to another without using physical conductors. The working principle of WET involves the use of electromagnetic fields to transfer energy between two or more devices. There are several main methods for WET, including electromagnetic induction, inductive resonance, and electromagnetic waves. We will discuss the working principles of WET using electromagnetic induction and inductive resonance in more detail.

Electromagnetic Induction

Electromagnetic induction is the most common method for WET, mainly used in wireless chargers for devices such as smartphones.

Work principle

1. Sender Coil (Primary Coil)
   A sending coil is installed in the charger. When alternating electric current (AC) flows through these coils, an alternating magnetic field is produced.
2. Receiving Coil (Secondary Coil)
   A receiving coil is placed on the device to be charged. The alternating magnetic field generated by the sending coil cuts the receiving coil and induces an electric current in it according to Faraday's law of electromagnetic induction.
3. Energy convertion
   The electrical current induced in the receiver coil can then be used to charge the device battery or operate the device directly.

According to Faraday's law, the electromotive force (EMF) induced in the receiving coil can be expressed as:

$$\varepsilon= -N ,d\varnothing\text{-}dt.$$

Where:
ε is the induced voltage
N is the number of turns in the receiving coil.
Φ is the magnetic flux through the coil.
dΦ/dt is the rate of change of magnetic flux.

Inductive Resonance

Inductive resonance uses electromagnetic resonance to increase the efficiency of energy transfer between two coils.

Work principle

1. Resonance Frequency
   The two coils (sender and receiver) are set to the same resonant frequency. This means that both coils oscillate at the same frequency, allowing for more efficient energy transfer.

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2. Resonance Field
   When the sending coil is fed with AC current at the resonant frequency, the resulting electromagnetic field can be captured more efficiently by the receiving coil which is also at the same resonant frequency.
3. High Efficiency
   Because both coils are in a state of resonance, energy can be transferred more efficiently and over longer distances than with conventional electromagnetic induction.

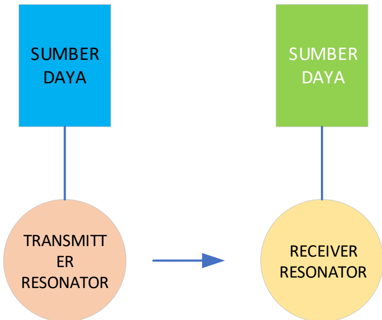

Figure 4. Block diagram of the principle of wireless energy transfer

The working principle of this system is based on the phenomenon of magnetic resonance of electromagnetic waves. When the transmitter resonator is fed by a power source, it generates a magnetic field that oscillates at the resonant frequency. This magnetic field will induce an electric current in the receiving resonator which has the same resonant frequency.

Because both resonators resonate at the same frequency, there is an efficient transfer of energy via electromagnetic waves propagating between them. The energy received by the receiving resonator can then be used to charge the connected load or electronic device. The energy transfer efficiency in an inductive resonance system can be described using the Q-factor equation:

$$Q=,1\text{-}R.,\text{-},L\text{-}C..$$

Where:
Q is the quality factor (Quality Factor)
R is the resistance in the circuit
L is the inductance of the coil
C is the capacitance in the circuit

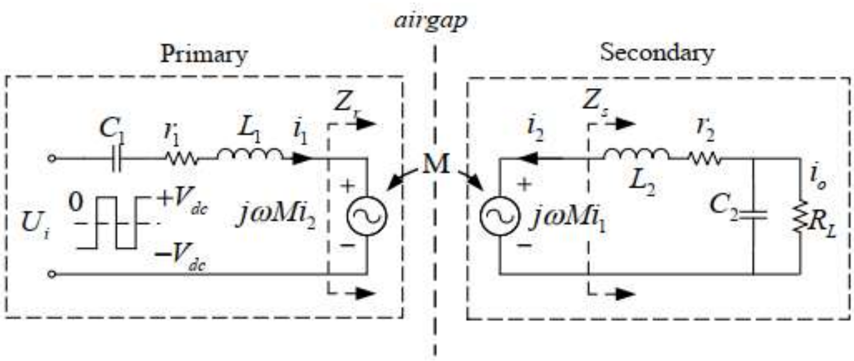

Figure 5. Equivalent circuit for wireless energy transfer

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The equation for the circuit in Figure 2.5 can be stated as follows:
On the primary side:

,𝑉-𝑖.= ,𝑉-𝑑𝑐.+𝑗𝜔,𝐿-1.,𝐼-1.+,1-𝑗𝜔,𝐶-1..,𝐼-1.+,𝑟-1.,𝐼-1.+ 𝑗𝜔𝑀,𝐼-2

On the secondary side:

0=,𝑟-2.,𝐼-2.+𝑗𝜔,𝐿-2.,𝐼-2.+,1-𝑗𝜔,𝐶-2..,𝐼-2.+𝑗𝜔𝑀,𝐼-1.+,𝑅 -𝐿.,𝐼-2

The equation of current and voltage on the primary side in the time domain is by changing equation (2.8) in Laplace form, we will get:

,𝑉-𝑖.,𝑠.=,𝑉-𝑑𝑐.+𝑠,𝐿-1.,𝐼-1.,𝑠.+,1-𝑠,𝐶-1..,𝐼-1.,𝑠.+,𝑟 -1.,𝐼-1.,𝑠.+𝑠𝑀,𝐼-2.,𝑠.

Then we change equation (2.9) into Laplace form, which will produce:

0=𝑠,𝐿-2.,𝐼-2.,𝑠.+,1-𝑠,𝐶-2..,𝐼-2.,𝑠.+,𝑟-2.,𝐼-2.,𝑠.+ 𝑠𝑀,𝐼-1.,𝑠.+,𝑅-𝐿.,𝐼-2.(𝑠)a

In that matrix can be written as follows:

,,𝑠,𝐿-1.+,1-𝑠,𝐶-1..+,𝑟-1.-𝑠𝑀-𝑠𝑀-𝑠,𝐿-2.+,1-𝑠,𝐶-2..+,𝑟-2.+,𝑅-𝐿...,,,𝐼-1.,𝑠.-,𝐼-2.(𝑠)..=,,𝑉-1.(𝑠).

Energy Transfer Equation The energy transfer between the transmitter and receiver resonator can be expressed by the equation:

𝑃= ,,𝜔.𝑀.,𝐼-1.,.𝐼-2..-,-,,,,𝜔-2..,𝐿-1..,𝐿-2.−,𝑀-2.. -

Where :
P = power transferred (watts)
ω = operating angular frequency (rad/s)
M = mutual coupling coefficient between resonators (Henry)
I_1 = current in the transmitter resonator (amperes)
I_2 = current in the receiving resonator (amperes)
L_1 = transmitter resonator inductance (henry)
L_2 = receiver resonator inductance (Henry)
Transmission efficiency can be expressed as follows:

𝜂=,,𝑅-𝐿.,𝐼-𝑜-2.-,𝑟-1.,𝐼-1-2.+,𝑟-2.,𝐼-2-2.+,𝑅-𝐿.,𝐼- 0-2.

In theory the system operates at the second resonant frequency which is determined by:

,𝜔-0.=,1-,-,𝐿-2.,𝐶-2...

METHOD

The research method used in this research is an experimental method with a quantitative approach. This approach enables thorough system evaluation through hands-on testing as well as numerical data analysis to gain accurate insights into system performance and efficiency. WET systems using the inductive resonance method will be designed based on specific application requirements. This design will include:

a. Component selection
   Coils, capacitors, and other electronic components will be selected based on operating frequency, transferred power, and desired transfer distance.
b. Design optimization
   Design parameters such as the number of coil turns, coil diameter, and distance between coils will be optimized to achieve maximum energy transfer efficiency.

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c. Simulation and analysis
Computer simulations will be carried out to predict the performance of the WET system and analyze the influence of various design parameters on energy transfer efficiency.

Implementation of the WET System

The designed WET system will be implemented by building a physical prototype. This prototype will consist of:

a. Sending network
The sending circuit will produce a high frequency power signal which will be induced into the receiving coil.

b. Coil
The coil will be used to generate and receive the magnetic field necessary for energy transfer.

c. Receiver circuit
The receiver circuit will convert the magnetic energy received into electrical energy that can be used by the load.

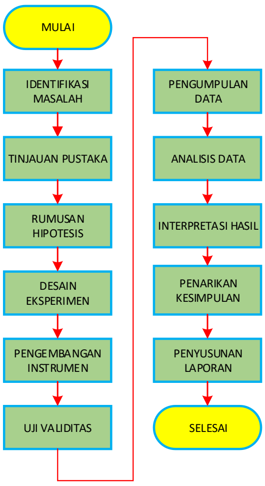

Figure 6. Research flow chart

To draw the Bode plot and step response of the transfer function that we have determined, we need to simplify the transfer function and convert it into a form that can be used using software such as MATLAB.

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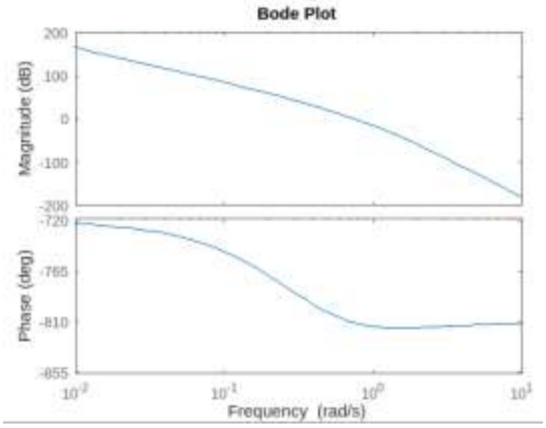

Figure 7. Bode plot of the system

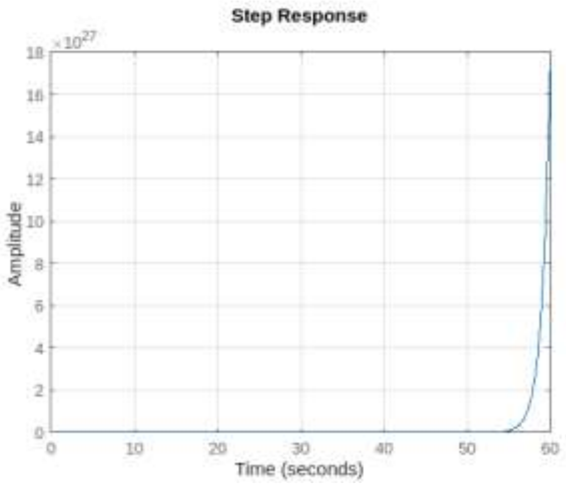

Figure 8. System response steps

The image above shows the Bode plot of the transfer function of the circuit we are analyzing. The bode plot consists of two graphs: one for the magnitude response and one for the phase response.

Magnitude Response

The magnitude graph (top) shows how the gain of the system changes with frequency. The y-axis shows magnitude in decibels (dB), and the x-axis shows frequency in radians per second (rad/s) on a logarithmic scale.

a. At low frequencies (around 10−2 rad/s), the magnitude is very high, indicating that the system has high gain at low frequencies.
b. The magnitude decreases as the frequency increases, indicating that the system has low-pass filter characteristics, where the gain decreases as the frequency increases.
c. At high frequencies (around 101 rad/s), the magnitude reaches very low values, indicating that the system attenuates high-frequency signals.

Phase Response

The phase graph (bottom) shows the phase change of the system with frequency. The y-axis shows the phase in degrees, and the x-axis shows the frequency in radians per second (rad/s) on a logarithmic scale.

a. At low frequencies (about 10−2 rad/s), the system phase is about -720 degrees.
b. As the frequency increases, the phase changes gradually to become less negative, but remains in the high negative range.
c. This phase change reflects the phase delay imposed by the system on its input signal.

ANALYSIS AND RESULT

Experiment Description

This chapter presents the results of research on wireless energy transfer (WET) and discusses the implications of the results obtained. The main focus is on the analysis of energy transfer efficiency over various distances and frequencies.

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Figure 9. Wireless energy transfer research circuit

This research uses a device as in Figure 4.1 with a frequency of 20 kHz and a certain configuration. Experiments were conducted under laboratory conditions with strict control of variables.

Experimental Results Data

Table 4.1 shows the results of measuring energy transfer efficiency at various distances. Figure 4.1 depicts a graph of efficiency versus distance.

Table 1. Energy Transfer Efficiency at Various Distances

Distance (cm)	Efficiency (%)
1	95
2	93
3	91
4	88
5	85
6	80
7	78
8	67
9	45
10	30

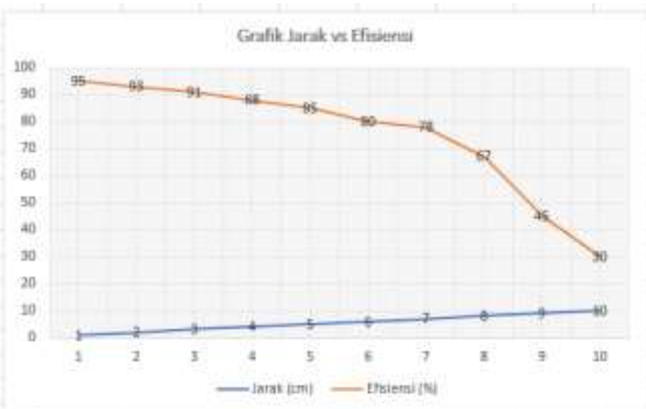

Figure 10. Distance vs efficiency graph

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Data Analysis

From the data obtained, it can be seen that the energy transfer efficiency decreases with increasing distance. At a distance of 1 cm, efficiency reaches 95%, while at a distance of 10 cm the efficiency drops to 30%. The results show that distance has a significant influence on energy transfer efficiency. The high efficiency at short distances indicates potential applications of WET in short-range devices. This research is consistent with a study by [1] which also found a decrease in efficiency with increasing distance. However, the efficiency obtained in this study was slightly higher due to the larger coil diameter and enamel wire diameter.

These results have important implications for the development of medical devices and gadgets that use WET, enabling charging without physical contact. In addition, these results also contribute to the literature on frequency optimization for maximum efficiency. This study was limited to distances up to 10 cm and fixed frequencies. Further research is needed to explore longer distances and wider frequency variations.

CONCLUSION

This research has evaluated the effectiveness and efficiency of wireless energy transfer using the inductive resonance method. From the results of the research carried out, several main conclusions can be drawn: Energy Transfer Efficiency: The inductive resonance method shows high energy transfer efficiency over a certain distance. This efficiency is influenced by factors such as the resonant frequency, the quality factor (Q-factor) of the coil, and the distance between the sending and receiving coils. Transfer Distance:This method is effective for energy transfer over medium distances, typically in the range of a few centimeters to several meters. The transfer efficiency decreases significantly as the distance between the sending and receiving coils increases. Resonance Frequency:Selection of the correct resonant frequency is critical to ensure optimal energy transfer. Higher resonant frequencies tend to provide better efficiency, but can also cause more electromagnetic interference.

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