

Comparative Study of Efficiency of Wireless Power Transfer Systems

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Abstract

A promising approach for transferring electrical energy without physical connectors is wireless power transfer, or WPT. Because of its uses in consumer electronics, electric vehicles, biomedical devices, and industrial automation, this technology has attracted a lot of attention. However, the transmission technique, distance, alignment, and operating frequency all have a substantial impact on power transfer efficiency. This research paper presents a comparative analysis of different wireless power transfer techniques, including inductive coupling, resonant inductive coupling, and microwave power transfer. The study assesses each method's effectiveness in several operational scenarios, including coil alignment, load circumstances, and distance variance. According to theoretical research and simulation, resonant inductive coupling performs better for mid-range applications, whereas inductive coupling delivers the maximum efficiency for short distances. Long-distance transmission is made possible by microwave power transfer, while the efficiency is reduced because of propagation losses. The findings offer guidance on choosing the best WPT technology for particular uses.

Keywords: Wireless Power Transfer, Inductive Coupling, Resonant Coupling, Microwave Power Transfer, Efficiency Analysis.

1. Introduction

Wireless power transfer (WPT) stands as a “proof to the boundaries of human ingenuity, demonstrating how energy, an entity traditionally bound by wires and physical connectors, can be transmitted over a distance without any visible connection” (IEEE, 2023). It is a concept that rethinks the fundamentals of power transmission, eschewing bulky cables and plugs in favour of a cleaner, more efficient method of energy distribution. This paradigm shift has enormous ramifications for a wide range of industries and, consequently, daily life.

WPT is the technique that enables electrical energy to be transferred from a power source to an electrical device without the use of physical connectors or cables. It is sometimes referred to as wireless energy transmission or wireless charging. This technology can offer a practical and effective way to charge or power a variety of gadgets, doing away with the need for conventional power connections (Tidwell, 2025).

The need for effective wireless power supply systems has grown significantly in recent decades due to the fast expansion of portable electronics, electric cars, and biomedical implants. Conventional wired charging solutions may have limited mobility, safety risks, and mechanical wear. Wireless charging improves convenience, dependability, and safety by doing away with cords. Efficiency is still one of the most important issues in wireless power systems, despite these benefits. In addition to being impacted by coil misalignment and environmental factors, power transfer efficiency declines with increasing transmission distance.

The objective of this research is to compare different wireless power transmission methods and examine their efficiency traits under various operating circumstances.

2. Literature Review

According to the Tesla science centre - “Nikola Tesla’s experiments with wireless transmission in the 1890s laid the groundwork for the world-changing technology of radio transmission. Guglielmo Marconi, initially credited with inventing the radio, received a patent in 1904 for his radio transmission system, earning him the Nobel Prize in Physics. But Tesla’s patents predated Marconi’s work. Tesla had filed key patents regarding radio transmission as early as 1897, with patents granted in 1900 (U.S. Patent Nos. 645,576 and 649,621). These patents covered fundamental aspects of wireless communication, including the use of tuned circuits for transmitting and receiving radio waves. In June 1943, almost five months after Tesla’s death, the U.S. Supreme Court ruled in Favor of Tesla (Tesla_science_center, 2025). Today, Tesla is recognized as a true pioneer of radio.” Henceforth, **Nikola Tesla** (Nikola, 1892) first investigated the idea in the late nineteenth century, when he showed that electrical energy could potentially be transmitted by electromagnetic fields.

Several researchers have examined the efficiency limitations of wireless power transmission methods. The idea of tightly coupled magnetic resonance for effective mid-range wireless power transfer was shown in a seminal work by **André Kurs** and other associates. Their study demonstrated that even when resonant coils were spaced many coil diameters apart, energy could still be effectively transferred between them. According to the research team- “Using self-resonant coils in a strongly coupled regime, we experimentally demonstrated efficient nonradiative power transfer over distances up to 8 times the radius of the coils (André, et al., 2007).” Over distances greater than two meters, they were able to transfer 60 watts with an efficiency of about 40% & concludingly they have recommended a quantitative model that describes the power transmission.

Researchers have focussed their objective towards solar power; and consequently, the solar power satellite (SPS) is emerged as an energy system. Infact, the solar cells gather sunlight, transform it into power, and then transport it from the geostationary orbit to the earth. Using transmitting and receiving antennas and wireless power transmission technology, which transmits electricity as a microwave to minimize transmission and distribution losses, the frequency ratio of energy is altered before being beamed to a receiver location on Earth and reconverted to electricity. **Naoki Shinohara** conducted further studies on microwave power transmission for long-distance wireless energy delivery, namely for solar power systems in space (Naoki, 2009).

Microwave power transmission for the geosynchronous orbit to the ground is one of the most important technologies for the SPS. This idea presents a significant opportunity for power transmission with minimal losses. It seems nearly inevitable that renewable energy sources will become more prevalent, with solar energy playing a significant role (Vaishnavi, 2020).

Several important factors influencing WPT efficiency have been found in earlier research, including: Coupling coefficient between transmitter and receiver coils, Quality factor of the resonant circuit, Operating frequency, Load impedance matching and Distance and alignment between coils. Not much has been accomplished since Tesla's work on wireless power technology. Presently we are using Mobile chargers and charging stations, these are the examples of wireless power transfer applications. The primary issue with wireless power is efficiency, which drastically decreases with even a slight increase in range.

3. Objective of the study and problem statement

Nowadays, cables are the primary means of transmitting the electrical energy that is accessible to all of us, but the efficiency of power transmission via wires is greatly diminished. The efficiency of electrical energy transfer is only 71%. Additionally, installing wires in remote areas is never easy. Even though wireless charging technologies have advanced significantly, a thorough comparison of various WPT approaches based on effectiveness and practical application is still required.

4. Principles of Wireless Power Transfer

Electromagnetic fields are typically used in wireless power transfer systems. Electrical energy is transformed by the transmitter into electromagnetic energy, which a receiver subsequently absorbs and transforms back into electrical power. The overall efficiency of a WPT system is defined as:

$$\eta = \frac{P_{out}}{P_{in}} \times 100$$

Where:

- P_{in} is the input power supplied to the transmitter
- P_{out} is the output power received by the load
- η is the power transfer efficiency

Different WPT methods use different mechanisms for transferring energy.

5. Wireless Power Transfer Systems

Wireless power transfer (WPT) systems are mainly categorized into two types: far-field (long-range) and near-field (short-range). In Near-Field (Non-Radiative) WPT Techniques, power transfers over short distances (typically within one wavelength or antenna diameter) using magnetic or electric fields. In the second category, Far-Field (Radiative) WPT Techniques transfer power over long distances (meters to kilometres) using electromagnetic waves, commonly referred to as power beaming.

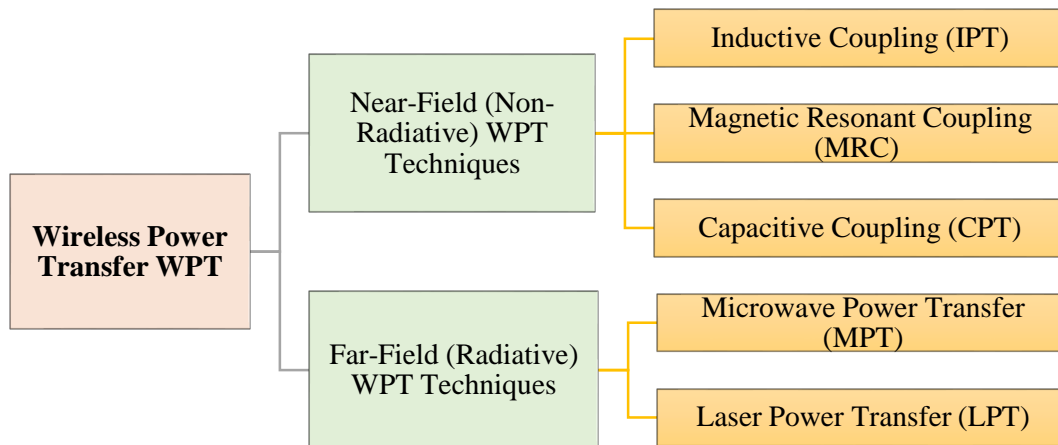


Figure 1: Categories of Wireless Power Transfer System

For this study only three types of power transfer system namely - Inductive Coupling, Resonant Inductive Coupling & Microwave Power Transfer have been discussed to an extent.

5.1 Inductive Coupling: The fundamental working principle is based on electromagnetic induction. When alternating current flows through the transmitter coil, it produces a time-varying magnetic field. This magnetic field induces voltage in the receiver coil according to Faraday's law of electromagnetic induction. It includes components: Power Source, Oscillator, Transmitter Coil, Receiver Coil, rectifier, and Load.

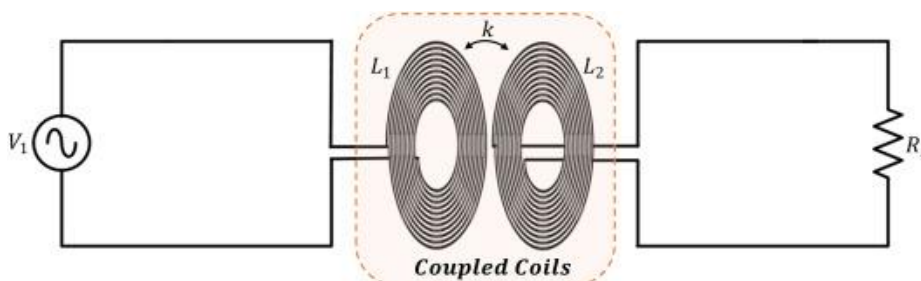


Figure 2: Block diagram of Basic Inductive Wireless Power Transfer System

[Source: (Science_direct, 2024)]

5.2 Resonant Inductive Coupling: Resonant inductive coupling improves power transfer efficiency by tuning both transmitter and receiver coils to the same resonant frequency. When the coils resonate at the same frequency, energy transfer becomes more efficient even at larger distances. It includes components: Capacitor, Inductor coil, Resonant circuit, and Load.

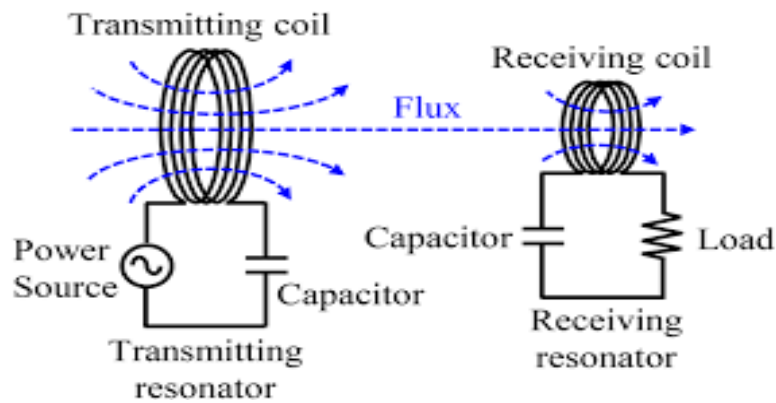


Figure 3: Block diagram of Resonant Wireless Power Transfer Circuit

[Source: (IET-Power-Electronics, 2019)]

5.3 Microwave Power Transfer: Microwave power transfer uses electromagnetic radiation to transmit energy over long distances. Electrical energy is converted into microwave signals, transmitted through antennas, and received by a rectifying antenna (rectenna). Microwave power transfer has long been the subject of research and testing. However, since Tesla, developments in wireless technology have enabled what was not feasible in the early 20th century. The transfer of power by microwaves over space is known as MPT. Specifically, an MPT system transforms direct current (DC) electricity into microwaves, which are then transmitted to a target, which then transforms the microwave radiation back into DC power (Brown & William, 1984). MPT include components like: Power Source, Microwave Generator, Transmitting Antenna, Rectenna, and Load. The block diagram of the MPT is shown in figure 3.

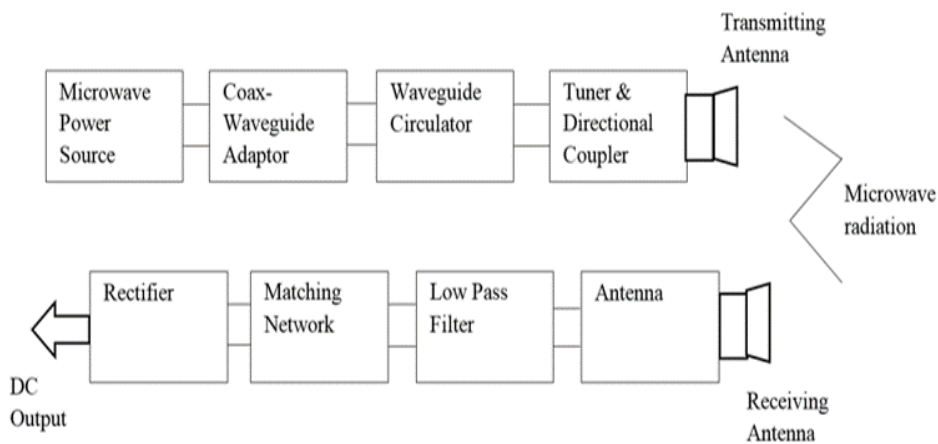


Figure 4: Block diagram Microwave Power Transfer System

[Source: (Venkateswara, Sai, & Venkat, 2013)]

A comparative performance of Inductive Coupling, Resonant Inductive Coupling & Microwave Power Transfer system has been shown in table 1.

Table 1: Comparative performance of Wireless Power Transfer (WPT) Systems

Wireless Power Transfer (WPT) Systems			
Parameter	Inductive Coupling	Resonant Inductive Coupling	Microwave Power Transfer
Transfer method	Inductive coupling is the most widely used wireless power transfer technique. It operates on the principle of electromagnetic induction, similar to a transformer	Resonant inductive coupling improves efficiency by tuning both transmitter and receiver coils to the same resonant frequency.	Microwave power transfer uses electromagnetic radiation to transmit energy over long distances.
Principle	Magnetic field between two Coils (near-field)	Coupled Magnetic resonators	Radiated electromagnetic waves (far-field)
Range	0 – 5 cm	5cm – 50 cm (can be extended)	Few Centimetres to Several meters
Efficiency	80 -90 % (high)	75 -85% (depends on Q-factors)	30-50% (distance dependent)
Power Handling	Watt to kW (consumer & EV)	kW (EV, Industrial)	Mega Watt to Watt (IoT sensors)
Alignment sensitivity	Very high (needs precise positioning)	Moderate (Misalignment tolerant)	Low (beam forming helps)
System Complexity	Simple coil design	Requires tuned resonant circuits	Complex antenna and circuitry
Cost	Low	Medium (tuning component5s)	Medium – High (RF hardware)
Size and weight	Compact Coils	Larger coil + resonators	Antenna Size depends on frequency
Safety	Low EMI, heating manageable	Emi manageable, resonant tuning	Potential EMI, Shielding needed
Advantages	High efficiency for short distances. Simple design and implementation. Widely used in consumer electronics.	Higher efficiency at moderate distances. Reduced sensitivity to coil misalignment. Suitable for high-power applications.	Long-distance energy transmission possible. Can power remote devices.
Applications	Smartphone wireless charging pads. Electric toothbrush chargers. Wearable device charging.	Electric vehicle wireless charging. Industrial robotics power supply. Wireless charging furniture.	Space solar power systems. Remote sensors. Military application.

<p>Real-world example</p>	<p>KAIST’s OLEV (Online Electric Vehicle) project – wirelessly charges buses/shuttles (20 – 25 kw) via road embedded coils. OLEV is developed by the Korea Advanced Institute of Science and Technology (KAIST), is an electric vehicle that can be charged while stationary or driving, thus removing the need to stop at a charging station. Operational in cities like Gwangju and Seol (KAIST_News, 2013).</p>	<p>WiTriCITY (Germany): 3.7 kW wireless charging for e-buses with approx. 90% efficiency over 20 cm gap. Components are 1. Power Hub: The Power Hub plugs into a standard wall outlet, or hardwired on a dedicated 15A circuit. Remains in standby mode until a cart enabled for wireless charging is parked above it. 2. Receiver: The Receiver installs under the cart in less than 30 minutes. It has connections to the battery and allows the WiTricity system to charge the battery wirelessly when positioned above the Power Hub (WiTricity, 2025).</p>	<p>A project is underway to build a low-cost microwave power transmission by 2030 in JAPAN. 10 countries along the equator have agreed to host a rectenna for 10 MW satellite delivering microwave power. Japan is spearheading the development of two promising technologies to make optimal use of both the Earth and space and fully harness the Sun’s power as electricity: space-based solar power and next-generation flexible solar cells (Japan_Government, 2023).</p>
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6. Results and Discussion

From the comparative chart shown above in table 1, we could list distance and efficiency of the wireless system, shown in table 2.

Table 2: Distance and efficiency of the WPT system

WPT Method	Distance Range	Efficiency	Major Loss Sources
Inductive Coupling	0 – 5 cm	80–90%	Magnetic leakage
Resonant Coupling	5 – 50 cm	75–85%	Resonance mismatch
Microwave Transmission	>1 m	30–500%	Radiation loss

[Source: Comparative Data from the work of Yahaya et al. (Yahaya, Adnan, & Kassim, 2018)]

Observations: from the above table it could be concluded that Inductive coupling provided the highest efficiency for very short distances. Whereas Resonant inductive coupling maintained stable efficiency over moderate distances. And Microwave transmission allowed energy transfer over long distances but suffered from significant propagation losses.

7. System Modelling and Simulation

For this study wireless power transfer systems (Inductive Coupling Vs Resonant Coupling) are being simulated using circuit modelling tools MATLAB to evaluate the efficiency. Equivalent circuit for the calculation of link efficiency is shown in figure 5 and simulation parameter is shown in table 3.

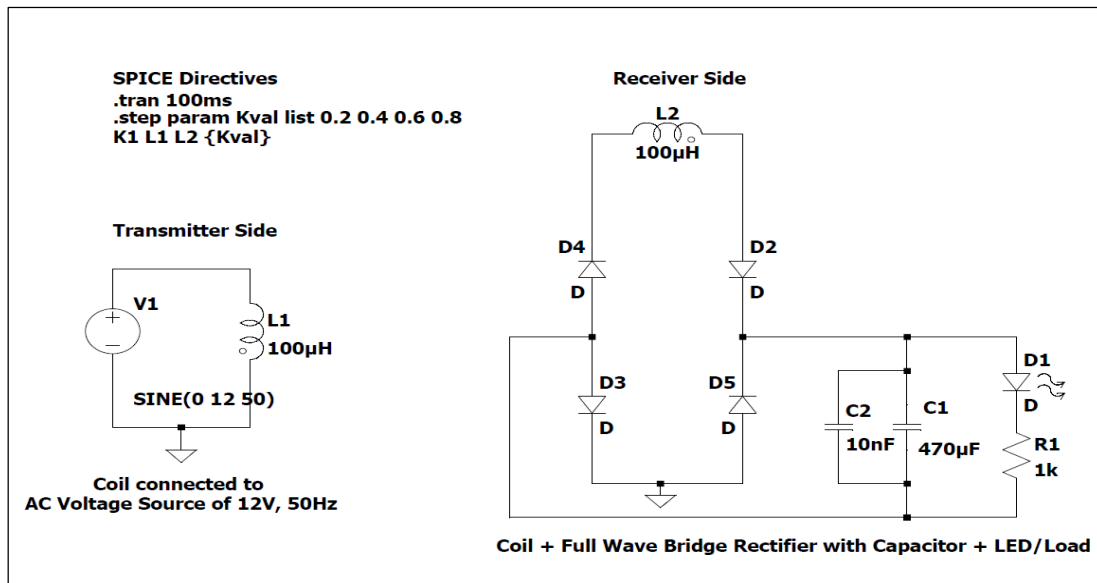


Figure 5: Equivalent circuit for the calculation of link efficiency.

The wireless power transfer system is designed and analyzed using LTspice. An alternating magnetic field is produced in this simulation by applying an AC sinusoidal voltage source to the transmitter coil (L1). Through magnetic coupling, this magnetic field causes a voltage to be induced in the reception coil (L2). A full-wave bridge rectifier made of diodes is then used to transform the induced AC signal at the receiver side into DC. A capacitor filter is used to smooth out the rectified output, which lowers ripples and produces a constant DC voltage. In order to demonstrate practical wireless power transmission, this DC output is then delivered to a load, which is represented by a resistor and an LED. When enough power is received, the LED illuminates.

Table 3: Simulation Parameters

Parameter	Value
Input Voltage	12 V
Operating Frequency	50 Hz
Coil Diameter	10 cm
Load Resistance	10 Ω

7.1 Input vs Output Waveform Analysis: The simulation results include a comparison between the input sinusoidal signal and the output voltage obtained after rectification. The output is a rectified and filtered DC signal, whereas the input signal is a pure sine wave. There are several output curves that correlate to various Coupling Coefficient (k) values. The induced voltage in the receiver coil rises in tandem with the coupling coefficient, leading to a greater DC output following rectification. The output voltage is low for lower coupling settings and could not be enough to efficiently drive the load. Improved power transfer efficiency is indicated by the output being steadier and reaching higher voltage levels as k increases. Figure 6 displays the waveform.

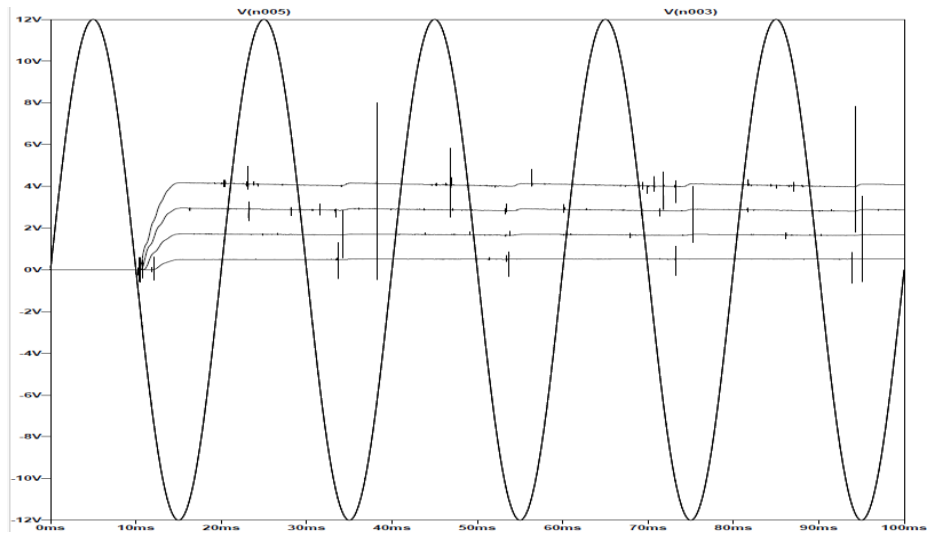


Figure 6: Input Vs Output wave form.

8. Efficiency Analysis

Efficiency was analysed by varying the following parameters:

1. Operating frequency
2. Distance between coils
3. Coil alignment

8.1 Efficiency vs Frequency: Inductive and resonant coupling systems exhibit quite different efficiency variations with frequency. Since there is no tuning mechanism to maximize energy transfer, the efficiency in inductive coupling is essentially constant over a large range of frequencies. Resonant coupling, on the other hand, shows a significant peak in efficiency at a particular frequency called the resonant frequency. The resonance principle, which states that inductive and capacitive reactance cancel each other out, governs this behavior. At this stage, the system attains optimal power transmission and maximum current, leading to extremely high efficiency. However, because to impedance mismatch and decreased energy transfer capacity, the efficiency drops as the frequency moves away from the resonant value. The efficiency vs. frequency data is shown in Table 4.

Table 4: Efficiency vs Frequency data from Simulation

----- Frequency Table -----		
Frequency_kHz	Eff_Inductive	Eff_Resonant
20	49.486	0.2767
29.474	55.333	1.4237
38.947	57.825	4.8423
48.421	59.083	12.935
57.895	59.8	28.522
67.368	60.245	51.548
76.842	60.54	75.332
86.316	60.744	91.371
95.789	60.892	97.819
105.26	61.002	98.017
114.74	61.086	95.407
124.21	61.152	91.943
133.68	61.205	88.487
143.16	61.247	85.353
152.63	61.282	82.618
162.11	61.311	80.266
171.58	61.335	78.254
181.05	61.356	76.531
190.53	61.374	75.05
200	61.389	73.772

Efficiency Table (Distance):

Distance_cm	Eff_Inductive	Eff_Resonant
1	70.915	98.997
1.4737	49.225	97.515
1.9474	29.809	94.503
2.4211	17.161	89.345
2.8947	9.9797	81.777
3.3684	6.0135	72.144
3.8421	3.7775	61.376
4.3158	2.4695	50.616
4.7895	1.6734	40.789
5.2632	1.1701	32.399
5.7368	0.84097	25.556
6.2105	0.619	20.136
6.6842	0.46525	15.91
7.1579	0.35617	12.64
7.6316	0.27713	10.112
8.1053	0.21877	8.1516
8.5789	0.17495	6.6242
9.0526	0.14154	5.4262
9.5263	0.11572	4.4796
10	0.095517	3.7259

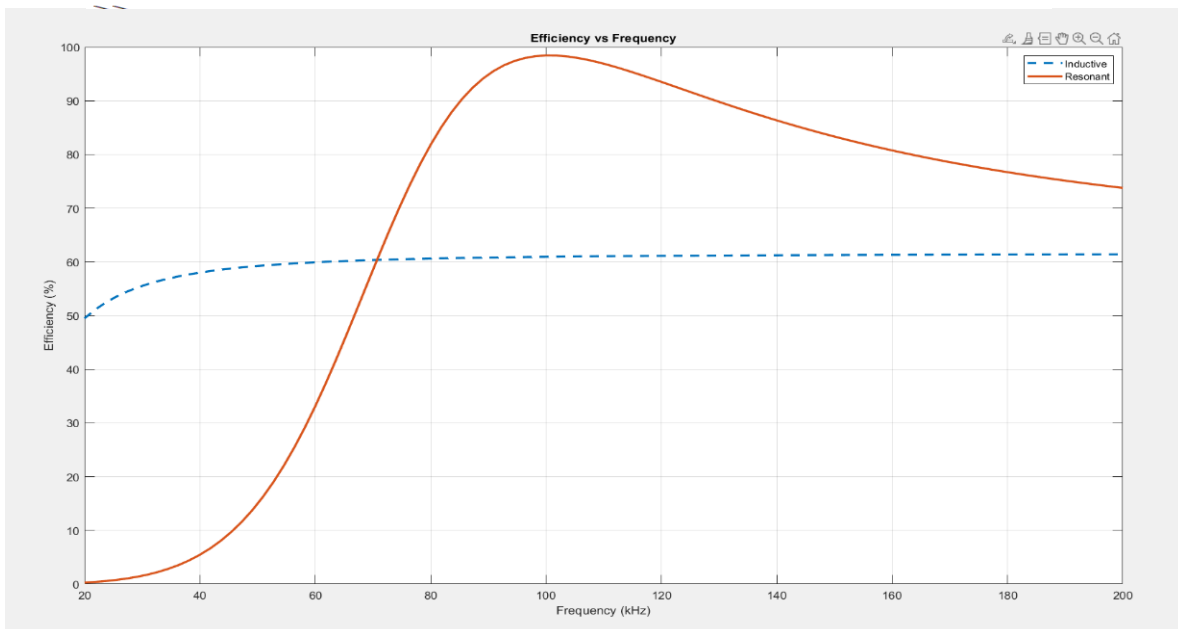


Figure 7: Efficiency Vs Frequency curve of WPT systems.

8.2 Efficiency vs Distance:

As the distance between the transmitter and receiver coils grows, wireless power transfer efficiency declines. This is mainly because there is less magnetic coupling between the coils, which reduces energy transfer. Magnetic coupling, in which the coupling coefficient rapidly diminishes with distance, governs the interaction. Even relatively slight increases in distance, efficiency in inductive coupling systems drastically decreases. However, because resonance facilitates more efficient energy transfer, resonant coupling devices function better across greater distances. However, due to inevitable field losses, efficiency inevitably declines as the distance increases, even in resonant systems. The efficiency vs. distance between the coil data from the simulation is shown in Table 5.

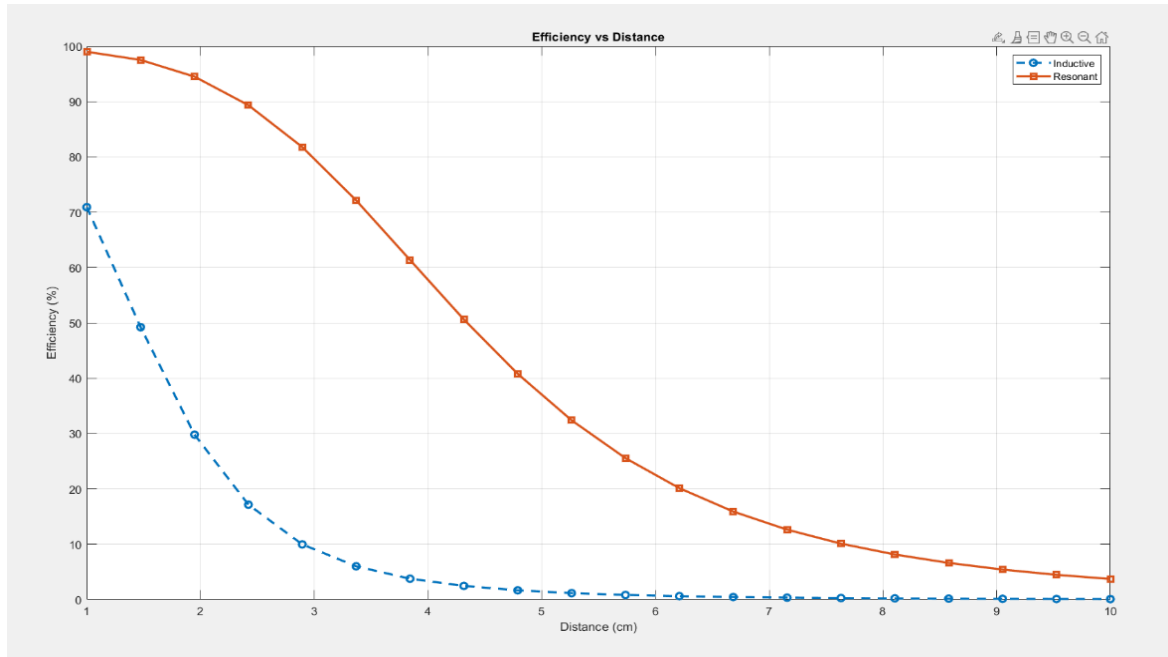


Figure 8: Efficiency vs. distance curve of WPT systems.

8.3 Efficiency vs Coil Diameter: An increase in coil diameter boosts wireless power transfer efficiency. This is due to the fact that a larger coil increases the mutual inductance between the transmitter and reception coils by producing a stronger and more widely dispersed magnetic field. A larger percentage of the magnetic flux generated by the transmitter links with the reception coil as the diameter grows, improving power transfer and efficiency. Nevertheless, not all of the magnetic flux produced is involved in the transfer of energy. Leakage flux is the part of the flux that is essentially lost because it does not couple to the secondary coil. Due to field spreading and faulty alignment, leakage flux increases together with the coil diameter, decreasing coupling efficacy. Larger coils also result in increased resistive losses. Consequently, after a given diameter, the efficiency starts to saturate and additional size increases only slightly boost it. The efficiency vs. coil diameter data from the simulation is shown in Table 6.

Table 6: Efficiency vs coil diameter data from Simulation

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===== Diameter Table =====
Diameter_cm      Eff_Inductive      Eff_Resonant
-----
2                17.62              18.527
2.4211          30.069             32.809
2.8421          42.442             48.114
3.2632          52.678             61.707
3.6842          60.252             72.364
4.1053          65.552             80.146
4.5263          69.185             85.643
4.9474          71.673             89.49
5.3684          73.395             92.19
5.7895          74.604             94.106
6.2105          75.467             95.484
6.6316          76.094             96.49
7.0526          76.557             97.235
7.4737          76.904             97.794
7.8947          77.167             98.221
8.3158          77.37              98.55
8.7368          77.528             98.807
9.1579          77.653             99.01
9.5789          77.752             99.171
10              77.832             99.301
    
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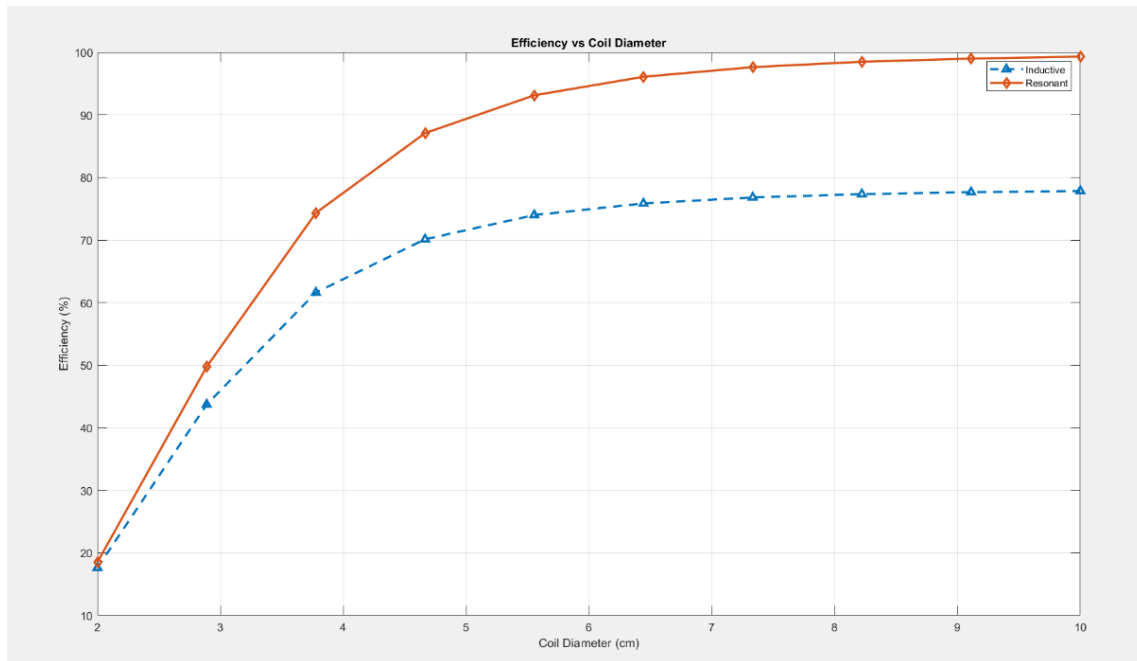


Figure 9: Efficiency vs. Coil Diameter curve of WPT systems.

9. Future Research Directions

The future advancements and research in wireless power transmission technology could be: AI-based power optimization algorithms and various approaches are combined in hybrid WPT systems. These developments have the potential to greatly boost efficiency and broaden the scope of wireless charging solutions.

10. Conclusion

Three main wireless power transmission methods were compared in this study: microwave power transfer, resonant inductive coupling, and inductive coupling.

The study evaluated the efficiency of inductive coupling and resonant inductive coupling under different operating conditions. The findings show that resonant inductive coupling performs better for medium-range wireless charging systems, whereas inductive coupling is the most effective technique for short-range applications. Long-distance energy transmission using microwave power transfer is still feasible, but more technological advancements are needed to improve efficiency and safety. The delivery of electrical energy in upcoming electronic systems could be completely transformed by wireless power transfer technology, which is still developing.

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