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Original Article

Experimental Analysis of Wireless Power Transfer Efficiency: Efficiency and Distance Show Inverse Relation

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Abstract *- Wireless power transfer technology uses magnetic fields to transmit power wirelessly between two devices. It has been well known as the method to transfer power conveniently, but its feasibility over longer distances has always been a question mark. This research paper presents an experimental analysis of the efficiency of wireless power transfer systems, focusing on the impact of distance between the transmitter and receiver coils, aiming to bring in data and certainty in the space of wireless power transfer. The study investigates the relationship between efficiency and distance, aiming to provide insights into the feasibility and practical limitations of wireless power transfer in real-world applications. The Efficiency measurements were recorded over a range of distances, from 1 mm to 20 mm, and logged at minute intervals for 20 minutes to observe the dynamic behavior of efficiency. The results indicate a gradual decrease in efficiency as the distance increases, with efficiency levels ranging from approximately 70.29% at 1 mm to around 36.29% at 20 mm. The efficiency can be curve-fitted with a linear equation of the form "y = a*x +b" using the curve_fit functionality of the SciPy library in Python. Additionally, the dynamic analysis reveals the system's settling time and stabilization of efficiency values at different distances. These findings provide essential insights for designing and optimizing wireless power transfer systems and emphasize the importance of distance in achieving efficient energy transmission in practical scenarios.*

Keywords *- Wireless power transfer, Efficiency, Distance, Power logger, Python scripting and Experimental analysis.*

1. Introduction

Wireless power transfer technology uses magnetic fields to transmit power wirelessly between two devices. The technology is based on magnetic induction between the planar receiver and transmitter coils [1]. The transmitter device generates a time-varying electromagnetic field that transmits power across space to a receiver device. The magnetic fields generate an alternating current within the receiving coil, which can then be utilized or converted as required. [2]. Wireless power transfer is a technology that has been around for a while. It has evolved and has become more efficient and practical. The invention of wireless power transfer can be traced back to the 19th century when Nikola Tesla demonstrated the concept of wireless power transfer [1]. Wireless power transfer technology, rooted in the principles of magnetic induction between planar coils, has evolved significantly since Nikola Tesla's 19th-century demonstration [1].

The use of wireless power transfer in the past was limited to charging small devices like toothbrushes and smartphones; however, with technological advancements, wireless power transfer has become more practical and is being used in various applications like electric vehicles [3]. Wireless power transfer has several advantages over traditional wired charging. It is safer as there are no exposed wires that can cause electrocution. It is also more convenient as it eliminates the need for cords, which can be messy and cluttered [4]. One of the challenges of WPT is to ensure compatibility and interoperability among different devices and charging systems [5]. Several wireless charging standards have been developed and adopted by various manufacturers and organizations to address this issue. These standards specify the technical requirements and parameters for WPT systems, such as frequency, power level, coil design, communication protocol, and safety measures [5]. Introducing standards like Qi and SAE has addressed interoperability concerns, specifying technical requirements for efficient power transfer over defined distances [5, 10]. Table 1 compares and looks at some wireless power transfer standards.

However, wireless charging is less efficient than charging with a cord, and wireless chargers need almost 50% more energy to charge your phone than wired chargers, wasting more energy [14, 15, 16]. The inefficiency of wireless charging is due to the losses in power between wirelessly charging devices [14]. To optimize product design according to the data gathered, researchers have investigated different methodologies for WPT, as well as advantages, disadvantages, and possible applications for each [13]. In addition, researchers have proposed various optimization designs for wireless charging systems based on magnetic resonance coupling [15].

This research addresses a critical gap in existing literature concerning wireless power transfer systems. While the technology's convenience for long-range applications is well-acknowledged, uncertainties persist regarding its efficiency and feasibility over significantly shorter distances [1] [2]. Previous studies lacked comprehensive experimental data and dynamic analyses to reveal the practical limitations of wireless power transfer. This paper contributes by presenting detailed efficiency measurements over a range of distances (1 mm to 20 mm), confirming the anticipated inverse relationship between efficiency and distance. Moreover, it introduces a novel empirical expression that is a valuable tool for predicting efficiency levels at distances beyond the experiment's scope, bridging a crucial gap in current understanding.

Table 1. Comparing wireless power transfer standards

Standard	Overview	Pros	Cons
Qi	World's de facto wireless charging standard for providing 5-15 watts of power to small personal electronics, primarily used to charge smartphones [6].	A universal, open standard that allows Qi-enabled devices from any manufacturer to connect to Qi chargers [7]. Applicable for electrical power transfer over distances of up to 40 millimeters (1.6 inches) [8].	Charging speeds are limited to 15 watts (9 volts, 1.67 amps), with 7.5 W and 10 W chargers being more common [9].
SAE	The first global standard that specifies, in a single document, both the electric vehicle- and supply equipment (EVSE) ground-system requirements for wireless charging of electric vehicles (EV) [10].	Allow for charging without the need for plugging in is widely considered a key enabler for accelerating the adoption of EVs and autonomous vehicles [10]. Three power levels were established: WPT1 (3.7 kW), WPT2 (7 kW), and WPT3 (11 kW) [5].	Limited to electric vehicles [10].
Qi2	The next generation of the Qi wireless charging standard is used in smartphones and other consumer tech to provide charging capabilities without the need to plug in a cable [11].	Uses magnets, or more specifically, a Magnetic Power Profile, allowing magnetic wireless power transfer [11]. Tight coupling allows for faster wireless charging [12].	The standard will initially launch with the same 15W limit, but higher power profiles will follow as the standard matures [12].

2. Methodology

2.1. Aim of the Study

The present research aims to conduct an experimental analysis of the efficiency of wireless power transfer systems and investigate the relationship between efficiency and distance between the transmitter and receiver coils.

2.2. Research Design

Apparatus: Wireless transmitter coil(10 turns of 1.08mm diameter copper wire with a ferrite backplate); wireless receiver coil(20 turns of the same 1.08mm copper wire, arranged in two layers of 10 turns each, stacked on top of one another without a ferrite backplate); 2 Arduino-based open source power loggers[17]; lab bench power supply; 10W, 10 Ohm power resistor. Python, SciPy, curve_fit. The two coils are held in place by 2 independent retort stands. The receiver coil is held stationary, whereas the transmitter coil is free to be moved to any distance.

This study adopts an experimental research design to investigate the efficiency of wireless power transfer. The independent variable is the distance between the transmitter and receiver coils, while the dependent variable is the efficiency of the wireless power transfer system. The efficiency is calculated using the formula: Efficiency(%) = (Power received/power transmitted) × 100. The study seeks to explore the changes in efficiency as the distance between the coils varies.

2.3. Hypothesis

H0 (Null Hypothesis): There is no significant relationship between the distance and efficiency of wireless power transfer.

H1 (Alternative Hypothesis): There is a significant relationship between the distance and efficiency of wireless power transfer.

2.4. Data Collection Procedure

1. Power Logging: Two open-source power logger projects [17] are used in the experiment – one connected to the transmitter and the other to the receiver. These loggers continuously measure and record the power on both the transmitter and receiver sides throughout the experiment.

2. Data Collection: The power log data is collected on separate SD cards for the transmitter and receiver. The SD cards are then transferred to a computer for further analysis. The data is collected and compiled into 2 .dat files, “Data.dat” and “Average.dat.”

2.5. Ethical Considerations

This research involves no human subjects or sensitive personal information. It focuses solely on the technical analysis of wireless power transfer efficiency using open-source hardware and software tools. No ethical approval is required for this study.

The detailed methodology outlined above comprehensively describes the experimental setup, data collection procedures, and data analysis using Python scripts. The systematic approach allows fellow researchers to replicate and validate the findings, contributing to advancing knowledge in the field of wireless power transfer.

3. Results

In the following section, the experimental analysis results are presented, detailing the relationship between efficiency and distance in wireless power transfer systems. The collected data, along with graphical representations and mathematical expressions, provide comprehensive insights into the system's behavior across varying distances.

The parameters being monitored here are efficiency (%) defined as (Power received/Power transmitted) × 100, and the distance between the 2 coils noted before each experiment. The experimental results are presented in Table 1, showing the efficiency at different distances between the transmitter and receiver coils. As expected, the efficiency decreases with an increase in distance, demonstrating the impact of the distance on the efficiency of wireless power transfer. At a distance of 1 mm, on average, the efficiency is approximately 70.28%. As the distance increases, the efficiency gradually decreases, reaching 36.29% at a distance of 20 mm.

Table 2. Efficiency of Wireless power transfer at several distances between Transmitter receiver coils over time (1mm-10mm)

	1mm	2mm	3mm	4mm	5mm	6mm	7mm	8mm	9mm	10mm
1 min	70.48	66.62	65.05	63.16	62.88	60.59	56.50	56.63	53.70	52.18
2 min	70.29	67.00	67.35	63.74	61.60	57.81	57.53	55.36	54.26	51.93
3 min	70.35	66.55	65.80	63.98	61.66	58.49	59.22	55.82	53.52	52.23
4 min	69.43	68.73	65.34	65.36	59.76	58.41	58.27	55.43	54.31	52.32
5 min	69.83	69.24	65.86	64.92	62.22	58.54	56.78	56.99	54.21	52.56
6 min	69.22	67.19	66.80	64.48	62.44	59.86	58.44	55.57	53.54	53.12
7 min	70.71	69.46	65.88	63.98	60.40	59.08	58.43	54.99	54.54	51.79
8 min	70.48	68.53	67.09	64.64	60.69	59.24	56.98	56.49	55.09	52.45
9 min	70.66	67.30	64.81	65.05	61.54	59.64	58.21	56.77	53.87	52.12
10 min	70.95	67.09	66.41	62.54	60.47	59.06	58.48	56.13	54.68	51.25
11 min	69.93	68.17	67.01	64.30	60.68	59.39	59.23	54.80	53.14	51.86
12 min	70.82	67.15	66.53	64.13	61.24	60.95	57.77	54.56	52.43	50.77
13 min	70.89	66.72	64.90	64.12	62.67	58.84	56.94	54.28	54.57	52.11
14 min	70.08	68.34	64.40	63.31	60.17	60.79	58.17	55.69	53.20	51.65
15 min	70.49	69.83	64.51	62.96	60.65	60.05	57.69	56.07	54.54	52.97
16 min	71.03	68.59	67.14	62.06	62.04	59.18	57.60	56.60	53.52	52.67
17 min	70.76	66.80	64.12	64.66	61.58	61.26	58.89	55.38	52.89	51.31
18 min	69.17	69.32	66.92	62.94	62.04	59.99	58.48	56.77	53.72	52.65
19 min	70.58	66.76	64.73	62.55	60.11	59.11	56.98	54.29	54.61	52.06
20 min	69.58	66.35	64.72	63.23	60.13	60.44	57.60	56.12	53.47	52.24

Table 3. Efficiency of Wireless power transfer at several distances between Transmitter receiver coils over time (11mm-20mm)

	11mm	12mm	13mm	14mm	15mm	16mm	17mm	18mm	19mm	20mm
1 min	50.55	49.37	47.43	44.97	42.83	42.15	40.21	39.21	37.16	36.61
2 min	48.97	47.62	47.77	45.46	43.28	42.01	40.98	38.25	37.45	36.55
3 min	51.39	48.19	46.28	45.14	43.25	41.99	40.34	38.91	37.34	35.92
4 min	51.04	49.25	45.82	45.81	42.64	41.71	40.83	38.62	37.38	36.16
5 min	49.89	47.78	46.62	46.02	43.75	42.42	40.81	39.27	37.54	36.15
6 min	49.08	48.82	47.89	45.00	42.97	41.80	40.16	38.55	37.53	35.92
7 min	49.76	48.81	47.03	44.71	43.81	41.61	40.05	39.22	37.37	36.18
8 min	50.82	48.82	46.52	44.61	43.79	42.45	40.49	39.12	37.68	36.14
9 min	50.43	48.93	46.21	45.00	42.87	42.87	40.84	39.58	37.38	36.72
10 min	50.94	48.52	46.22	44.96	43.81	41.32	39.80	39.26	37.93	36.83
11 min	49.40	48.60	45.94	45.22	44.11	41.46	39.90	39.08	37.91	36.76
12 min	49.89	48.84	47.03	44.43	43.31	42.22	39.98	39.43	37.22	36.24
13 min	50.56	49.78	47.47	44.47	42.77	41.55	41.03	39.71	37.86	35.77
14 min	49.48	49.03	46.56	44.36	43.76	41.75	39.98	38.73	37.52	36.23
15 min	50.50	48.48	47.45	44.32	44.03	41.20	40.65	39.28	37.59	36.89
16 min	50.37	48.45	47.21	45.30	43.80	41.26	40.41	38.83	37.41	36.08
17 min	50.64	47.72	46.44	45.98	42.98	42.49	40.54	38.80	37.34	36.00
18 min	49.85	48.84	47.58	46.01	44.36	42.4	41.04	39.27	37.33	36.59
19 min	49.84	48.85	46.42	45.72	43.68	41.75	40.19	39.05	37.99	35.98
20 min	50.53	48.01	46.85	44.31	43.92	42.29	40.50	38.26	37.23	36.20

Table 4. Average efficiencyof Wireless power transfer at several distances between Transmitter and receiver coils

1mm	70.29%
2mm	67.79%
3mm	65.77%
4mm	63.81%
5mm	61.25%
6mm	59.54%
7mm	57.91%
8mm	55.74%
9mm	53.89%
10mm	52.11%
11mm	50.20%
12mm	48.63%
13mm	46.84%
14mm	45.09%
15mm	43.49%
16mm	41.94%
17mm	40.44%
18mm	39.02%
19mm	37.51%
20mm	36.30%

Figure 1 illustrates the efficiency of the wireless power transfer system at different distances logged over a span of 20 minutes, measured at each minute interval. This dynamic analysis allows us to observe how the efficiency changes over time as the system stabilizes at various distances. The efficiency curve for each distance showcases the initial settling period, followed by a relatively stable efficiency value. The graph confirms that efficiency tends to stabilize after a brief period and maintains a consistent level during the observation time.

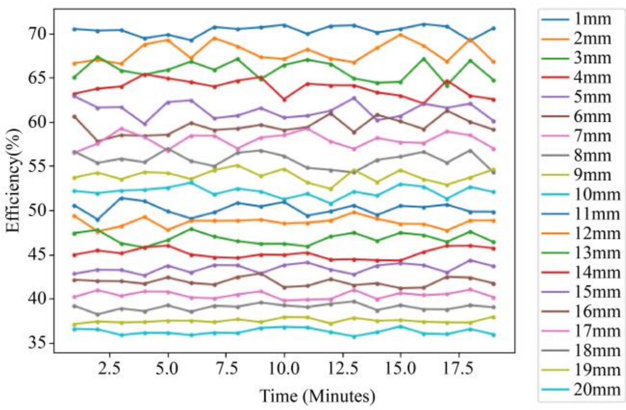

Fig. 1 Graph of efficiency vs time of several distances between transmitter and receiver coil using the below code

Figure 1 is generated using the code below

```
import numpy as np
import matplotlib.pyplot as plt

data = np.loadtxt("Data.dat", delimiter=" ",
comments="#")
```

```
time = data[0:19, 0]
for i in range(1, 21):
  plt.scatter(time, data[0:19, i], s=5)
  plt.plot(time, data[0:19, i], label=str(i)+'mm')

plt.title("Efficiency vs Time")
plt.xlabel("Time (Minutes)")
plt.ylabel("Efficiency(%)")
plt.legend(bbox_to_anchor=(1.05, 1), loc='upper left',
borderaxespad=0)
plt.show()
```

Figure 2 displays the relationship between the distance between the transmitter and receiver coils and the corresponding efficiency of the wireless power transfer system. The efficiency decreases as the distance increases, consistent with the theoretical expectations. The graph shows a gradual decline in efficiency from approximately 70.28% at a distance of 1 mm to around 36.29% at 20 mm. This demonstrates the impact of distance on the overall efficiency of the wireless power transfer system.

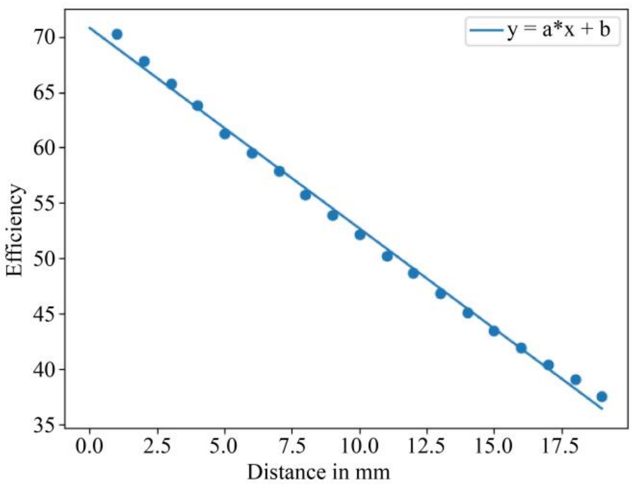

Fig. 2 Graph of efficiency vs distance generated by the code below

Figure 2 is obtained using the code below.

```
import numpy as np
import matplotlib.pyplot as plt
from scipy.optimize import curve_fit

data = np.loadtxt("Average.dat")

distance = data[0:19, 0]
efficiency = data[0:19, 1]

def func(x, a, b):
  return a*x + b

# fit curve
popt, pcov = curve_fit(func, distance, efficiency)

x_new = np.arange(min(distance) - 1, max(distance) + 1,
1)
# unpack optima parameters for the objective function
a, b = popt
# Standad Deviation
std_deviation = np.sqrt(np.diag(pcov))
# use optimal parameters to calculate new values
y_new = func(x_new, a, b)

print("The equation of fit-curve is: y = " +
    str(round(a, 2)) + "x + " + str(round(b, 2)))
print(std_deviation)
plt.scatter(distance, efficiency)
plt.plot(x_new, y_new, label="y =  a*x + b")
plt.xlabel("Distance in mm")
plt.ylabel("Efficiency")
plt.title("Efficiency vs Distance")
plt.legend()
plt.show()
```

4. Curve Fitting and Empirical Expression

Using the collected data, a curve fitting technique was applied in Python to find a mathematical expression that best represents the efficiency as a function of distance by using the curve_fit functionality of the scipy library. After analyzing the data points and fitting various models, the empirical expression “-1.81x + 70.79” was obtained, where ‘x’ represents the distance in millimeters. The expression takes the form of “ax + b,” with ‘a’ being the coefficient of the distance term and ‘b’ being the y-intercept representing the efficiency when the distance is 0. The obtained empirical expression effectively captures the efficiency trends as the distance varies, providing a mathematical relationship between the distance and the corresponding efficiency.

The derived empirical expression allows for convenient estimation of the efficiency levels at different distances beyond the range of the experimental measurements. It serves as a useful tool for predicting the efficiency of wireless power transfer systems for specific distances, facilitating the design and optimization of such systems for various practical applications. The presented mathematical expression, “-1.81x + 70.79,” enhances the understanding of the efficiency-distance relationship, providing valuable insights into the performance limits and potential improvements for wireless power transfer systems. This information will be instrumental in advancing the development and implementation of wireless power transfer technologies in real-world scenarios.

5. Discussion

Both Figure 1 and Figure 2 support the key findings presented in Table 1, emphasizing the inverse relationship between distance and efficiency in wireless power transfer systems. Graph 1 offers an insight into the transient behavior of efficiency at different distances, shedding light on the time the system takes to stabilize and achieve consistent efficiency values. On the other hand, Graph 2 visually represents the efficiency trend, demonstrating how the system’s performance degrades with greater distances.

These graphical representations enhance the understanding of the experimental results and provide valuable visual evidence to support the conclusions drawn in this research. The observed trends underscore the importance of optimizing the distance between the transmitter and receiver coils to achieve the desired efficiency levels in practical applications of wireless power transfer technology.

The analysis includes a crucial aspect: the derived empirical expression, "-1.81x + 70.79." This mathematical representation effectively captures the efficiency as a function of distance. By applying curve fitting to the collected data, this expression not only enhances our understanding of the system's behavior but also provides a predictive tool for estimating efficiency levels beyond the range of experimental measurements.

6. Conclusion

This research paper presents experimental data on the efficiency of wireless power transfer at various distances between the transmitter and receiver coils. The results demonstrate a clear inverse relationship between distance and efficiency, highlighting the importance of optimizing the distance for effective wireless power transfer applications. These findings can serve as a valuable reference for designing and implementing wireless power transfer systems, considering the trade-offs between distance and efficiency to meet specific requirements in practical scenarios.

Despite the valuable insights gained from this research, certain limitations should be noted. Firstly, the experimental analysis focused on a controlled environment, and real-world conditions, such as electromagnetic interference and varying load characteristics, were not fully explored. Additionally, the empirical expression derived from curve fitting provides a generalized understanding of efficiency trends, but individual system variations and component tolerances could impact its accuracy. Future studies could address these limitations by conducting experiments in diverse environments and considering a broader range of system parameters. Despite these limitations, our findings significantly contribute to understanding and optimizing wireless power transfer systems.

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