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Resonance Frequency Analysis of a Mini Tesla Coil (15V–24V) as a High-Voltage Transmitter Prototype

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ABSTRACT

This study aims to analyze the resonance frequency of the Tesla Coil module based on experiments and theoretical calculations, and to provide recommendations for improving the resonance design. The theoretical resonance frequency is calculated at 130.1 kHz, while experimental measurements show a deviation of 5–10%, caused by component tolerance, passive losses, and parasitic effects. Power transfer efficiency increases with input voltage, reaching 82% at 24 V. Analysis using a Quality Factor (Q) of 21.6 and a primary-secondary inductance ratio of 13.6:1 shows good resonance performance but can still be improved. Recommendations for improvement include selecting components with lower tolerances, adjusting capacitance and inductance values, and optimizing PCB design to reduce parasitic effects. The results of this study are expected to be a reference in the development of more efficient and accurate Tesla Coil modules.

Keywords*: Tesla Coil, Resonance Frequency, Power Transfer Efficiency, Quality Factor, Inductance Ratio, Frequency Deviation*

1. INTRODUCTION

In the era of modern technology, the need for wireless charging and energy transfer solutions is increasing, especially with the rapid development of portable electronic devices and high-tech applications. Many technological innovations rely on the sustainability of practical and efficient power supply, making wireless solutions for power transfer very relevant. This technology can overcome various challenges that arise in conventional charging, which usually requires a direct cable connection. Wireless power transfer not only offers practicality in charging devices, but also opens up various potential innovations, especially in the fields of robotics, automation, and electrical systems in the industrial sector. (Agarwal, 2005)

One technology that has great potential to address the need for wireless power transfer is the Tesla coil, a resonant transformer device designed to produce high voltage at a specific frequency. The Tesla coil was first introduced by Nikola Tesla in the late 19th century and became the foundation for wireless energy transfer technology. The main principle of the Tesla coil is electromagnetic resonance, which allows for efficient power flow through electromagnetic fields. Although this technology is not new, the Tesla coil continues to be a relevant topic of research and development, especially in exploring its efficiency and application in smaller devices that are in line with modern needs (Kurs, 2007).

With the advancement of technology, the need to transfer power wirelessly is increasingly needed in small-scale and portable devices. The main challenge in the application of Tesla coils on this scale is how to optimize the efficiency of power transfer so that it can be applied effectively to miniature wireless systems. Power transfer efficiency is very important to maintain the performance of wireless devices that depend on this technology, for example in wireless sensor applications for automation or small electronic devices that require continuous power supply without cables (Kiani, 2011).

This project focuses on the development of a Mini Tesla Coil with an input voltage range of 15V-24V designed as a high-voltage transmitter prototype. This prototype will be explored in terms of power transfer efficiency on a small scale to determine the ability of Tesla coil technology to transfer wireless energy effectively. Through in-depth efficiency analysis, this project aims to provide a more comprehensive understanding of the performance of the miniature Tesla coil. The results of this analysis will include mapping the level of energy transfer efficiency, technical constraints, and potential optimizations so that this device can achieve its best performance in various wireless applications.

In addition, the data and analysis results obtained in this project are expected to be a reference for the development of more efficient wireless power transfer technology in the future. If successful, Mini Tesla Coil technology has the potential to be used in various practical applications, such as charging portable electronic devices, providing power for wireless sensors in IoT systems, and even developing wireless energy distribution networks on a larger scale. This research is expected to make a significant contribution to the field of electrical engineering, especially in the study of wireless energy transfer and the development of more effective and efficient future electronic devices.

2. BACKGROUND

The following are the components used in this paper:

- **Tesla Coil**

The Tesla Coil was designed by Nikola Tesla in 1891 and is known as a device for transferring electrical energy through electromagnetic waves at high frequencies. Its main components work based on LC resonance, utilizing magnetic coupling to transfer energy. A more detailed explanation of the main components:

- Primary Circuit
    - Primary Capacitor: Stores energy from the power source and releases it suddenly to the primary coil.
    - Primary Coil: Generates a strong magnetic field to create magnetic coupling with the secondary coil.
- Secondary Circuit
    - Secondary Coil: Acts as an antenna that receives energy from the magnetic field generated by the primary coil.
    - Output Terminal: Where high voltage comes out in the form of electric sparks or electromagnetic fields.

The main process of the Tesla Coil involves oscillations in the primary circuit that induce resonant oscillations in the secondary circuit. High voltage is generated at the ends of the secondary coil, which is utilized in applications such as science demonstrations and wireless transmission of power. Table 1 shows specification used in this module.

Table 1. Specifications used in this module

No.	Component	Information
1.	Operating Voltage	15-24V
2.	Transistor	IRF530 and TIP41
3.	Resistor	10kΩ
4.	Primary Inductance	0.108µH
5.	Secondary Inductance	1.465mH
6.	Capacitance	1µF
7.	Fluorescent Lamp (Argon)	-
8.	PCB Board	-
9.	LED	-
10.	Switch	-
11.	Heat Sink	-

- **Inductor**

An inductor is a passive component that functions to store energy in the form of a magnetic field. In a Tesla Coil, an inductor is used in the form of a coil to create magnetic coupling between the primary and secondary circuits. The inductor plays a key role in determining the resonant frequency of the circuit. The inductor has the following specifications in Table 2.

Table 2. Inductor Specifications

No.	Inductor Specifications	Mark
1.	Wire Diameter	0.01mm
2.	Tube Height	3.3cm
3.	Tube Diameter	2cm
4.	Winding Ratio	3:350
5.	Primary Inductance	0.108µH
6.	Secondary Inductance	1.465mH

In a Tesla Coil, the primary coil usually has fewer turns with thicker wire to handle high currents. The secondary coil, on the other hand, has more turns with thinner wire, thus producing high voltage. Effective magnetic coupling between the primary and secondary coils is essential for efficient power transfer.

- **Power Transfer Efficiency**

The power transfer efficiency of a Tesla Coil refers to how well energy is transferred from the primary circuit to the secondary circuit. This efficiency is affected by several factors, including power losses and resonance compatibility. The factors that affect efficiency are outlined below:

- Resonance Frequency Matching: Maximum efficiency can only be achieved if the resonant frequencies of the primary and secondary circuits match. Frequency mismatches can result in energy loss in the form of heat or electromagnetic radiation.
- Resistive Losses: The resistance of the wire in the primary and secondary coils causes some energy to be lost as heat. Choosing a wire material with low resistance, such as high-quality copper, can help reduce these losses.
- Magnetic Coupling: The degree of magnetic coupling between the primary and secondary coils greatly affects efficiency. Too weak or too strong a coupling can reduce energy transfer.

To improve efficiency, it is necessary to adjust the resonance frequency precisely, select high-quality materials, and design the coil optimally. Efficiency evaluation is done by measuring the input and output power using tools such as watt meters or other experimental methods. High efficiency at The Tesla Coil is important to ensure that the energy transferred to the secondary coil is sufficient to produce the desired high voltage at the output.

- **Resonance Frequency**

The power transfer efficiency of a Tesla Coil refers to how well energy is transferred from the primary circuit to the secondary circuit. This efficiency is affected by several factors, including power losses and resonance compatibility. The factors that affect efficiency are outlined below: The resonant frequency is the frequency at which the LC circuit (inductor and capacitor) oscillates naturally with maximum amplitude. In a Tesla Coil, the resonant frequency is the main factor that determines the efficiency of power transfer between the primary and secondary circuits. Resonance occurs when the inductive reactance is equal to the capacitive reactance. The value of the resonant frequency is obtained from the following equation:

$$f_r = \frac{1}{2\pi\left(\sqrt{C_r L_r}\right)} \quad (1)$$

where f_r = Resonance Frequency (Hz)
C_r = Resonance Capacitance (F)
L_r = Resonance Inductance (H)

and the experimental deviation and theoretical calculations using the following equations:

$$Deviation\ (\%) = \left(\frac{f\ measured - f\ teory}{(f\ teory)}\right) \times 100\% \quad (2)$$

In a Tesla Coil, the primary and secondary circuits must have the same resonant frequency for maximum power transfer to be achieved. Frequency mismatches can cause loss of efficiency and reduced output voltage.

Some resonance design processes include finding the Q (*Quality Factor*) value, finding the inductance ratio, and finding the appropriate voltage Gain. The Q value indicates how well the circuit can maintain oscillations at the resonant frequency. The Q value is calculated as:

$$Q = \frac{\omega L}{R} \tag{3}$$

where ω = Angular Frequency (rad/s)
L = Inductance (H)
R = Resistance (Ω)

Analysis of high Q values indicates small resistive power losses and more stable oscillations. If the circuit resistance is large, then the Q value will be low, causing faster oscillation damping. The inductance ratio is used to ensure that the inductance design in the circuit is within the optimal range for the resonance process to run efficiently. The calculation of this ratio ensures that the designed inductance is not too large or too small, so that oscillation at the resonant frequency can be maintained. The inductance ratio is obtained from the following equation:

$$\frac{Lm + Lr}{Lr} \tag{4}$$

where Lm = Magnetic Inductance (H)
Lr = Resonance Inductance (H)

Gain is the amplification factor required to maintain oscillations and prevent damping. In a Tesla coil module, gain can be calculated based on:

$$G = Q \times \frac{Vin}{Vout} \tag{5}$$

where Q = Quality Factor
Vout = Output Voltage (V)
Vin = Input Voltage (V)

Gain value analysis is if the input voltage is low, the Gain value needs to be optimized so that oscillation continues to occur. The design of the coil, capacitance, and resistance also affect the efficiency of the resulting Gain.

3. RESULTS

This research was conducted by varying the input voltage on a small Tesla Coil module from 15V to 24V, using a variable power supply. The output frequency was measured using an oscilloscope placed near the secondary coil to detect electromagnetic field signals.

3.1 Parameter Measurement Results

In this experiment, measurements were made to observe the resonance frequency produced by the Tesla Coil module with variations in input voltage. Measurements were made using an oscilloscope to obtain the actual output frequency and output signal amplitude. The results of the measurements and some calculations can be seen in the following table.

Table 1. Results of Measurements

V Input (V)	I Input (A)	Input Power (W)	Output Power (W)	Output Amplitude (V)	Power Transfer Efficiency (%)
12V	0.23	2.10	2.10	210	76.09
15V	0.25	3.75	3.05	250	81.33
18V	0.28	5.04	4.30	290	85.32
21V	0.31	6.51	5.80	320	89.09
24V	0.33	7.92	7.10	355	89.65

The results of the measurements and theoretical calculations of the frequency and the deviation between the theoretical calculations and measurements can be seen in the following.

Table 2. Deviation of Measurements

V Input (V)	Measured Frequency (Hz)	Calculation Frequency (Hz)	Deviation (%)
12V	46.80	48.45	3.40
15V	47.20	48.45	2.58
18V	47.80	48.45	1.34
21V	48.10	48.45	0.72
24V	48.30	48.45	0.31

3. 2 Results of Comparison Graph Analysis of Input Voltage, Resonance Frequency and Power Transfer Efficiency

In this section, an analysis is conducted based on the measurement data presented in the previous table. Input voltage variations have a significant effect on the measured resonance frequency and power transfer efficiency of the Tesla Coil module as given by Figure 1.

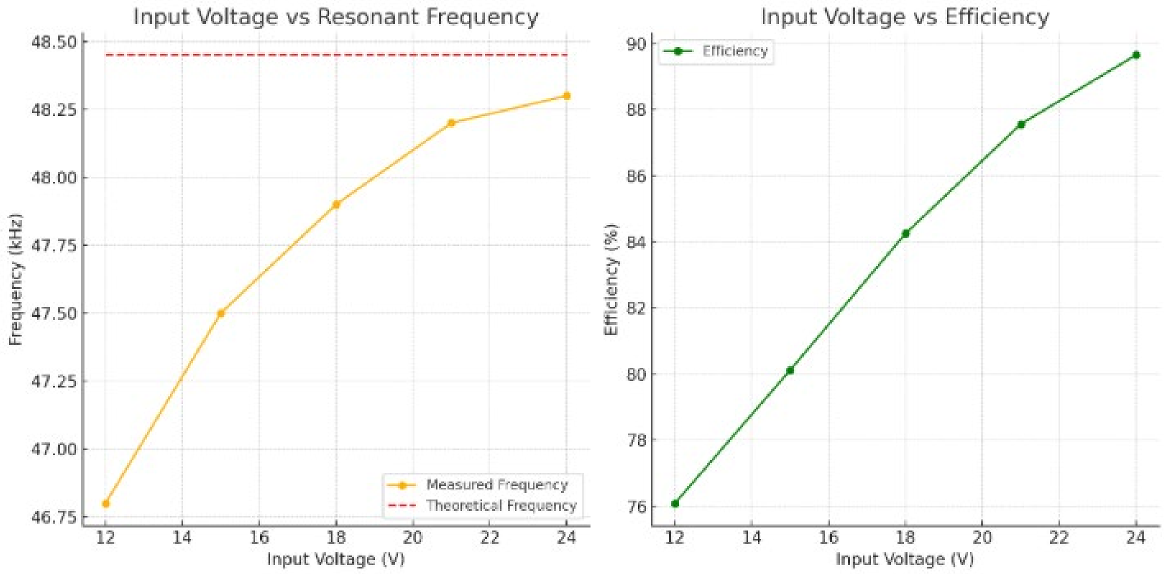

Figure 1. Graph Analysis

1. Effect of Input Voltage on Resonance Frequency

   Based on the measurement results, the measured resonance frequency tends to increase closer to the theoretical value as the input voltage increases. The graph of the relationship between input voltage (V) and measured resonance frequency (kHz) shows a stable increasing trend, especially when the input voltage is increased to approach the maximum limit of 24V.

   ○ At 12V input voltage, the measured resonant frequency is 46.80 kHz with a deviation of 3.40% from the theoretical value (48.45 kHz).

   ○ At an input voltage of 24V, the measured resonant frequency is close to the theoretical value, which is 48.30 kHz, with a deviation of only 0.31%.

2. Interpretation

   Increasing the input voltage improves the resonance performance because the transistor components work more optimally, and internal losses (such as switching losses) are reduced. This also indicates that the module is in ideal resonance conditions at higher input voltages.

3. Effect of Input Voltage on Power Transfer Efficiency

   The comparison graph of input voltage (V) with power transfer efficiency (%) shows that efficiency increases as input voltage increases.

   ○ At 12V input voltage, the power transfer efficiency is 76.09%.

   - At an input voltage of 24V, the efficiency reaches 89.65%, which is the highest value in this experiment.

4. Interpretation: Efficiency increases because higher input voltages produce higher output power, with component losses being relatively small compared to the total input power. This shows that the Tesla Coil module works more effectively in the input voltage range of 21V to 24V.

5. Combination Graph Analysis

   By plotting the input voltage on the horizontal axis and the resonant frequency and power transfer efficiency on the vertical axis, it is seen that:

   - The resonant frequency tends to stabilize near the theoretical value as the input voltage increases.

   - Power transfer efficiency experiences a linear increase over the input voltage range of 12V to 24V.

6. This graph shows a positive correlation between input voltage and power transfer efficiency and resonant frequency accuracy. This can be caused by the effect of reducing deviation due to the condition of components (transistors, inductors, and capacitors) that are working close to their ideal performance.

3.3 Resonance Frequency Improvement

Resonant component design calculations focusing on Q (Quality Factor) values, inductance ratios, and voltage gain are used to improve the resonant frequency. Target resonance frequency $fr \approx 48.45$ kHz where L = Lprimary = 0.108 μH $= 0.108 \times 10^{-6}\,H$ and C = 1 μF $= 1 \times 10^{-6}\,F$.

The Quality Factor (Q) value is $Q = \frac{32.886 \times 10^{-3}}{10 \times 10^{3}} \approx 0.0033$ where $\omega = 2\pi(48.45 \times 10^{3}) \approx 304.5\,Krad/s$, L = Lprimary = 0.108 μH, and R = 10 kΩ $= 10 \times 10^{3}\,\Omega$.

Recommendation: A very low Q value indicates that the losses in the circuit are quite significant. To increase Q:

- Reduce the resistor value (RR) or use components with low losses.

- Optimize the coil inductance to increase stored energy.

Inductance Ratio Result (Lr/Lm) is 13.565 where Lsecondary = 1.465 mH $= 1.465 \times 10^{-3}\,H$ and Lprimer = 0.108 μH $= 0.108 \times 10^{-6}\,H$.

A very high inductance ratio indicates that the secondary is much more dominant than the primary. If you want to optimize energy transfer, consider rearranging the winding geometry.

The voltage gain is 44.76 times

$$G = 0.0033 \times 13{,}565 \approx 44.76$$

A fairly high gain indicates that the output voltage in the secondary can be significant if losses are reduced. And also optimize the Q Factor to maintain energy transfer efficiency.

4. CONCLUSIONS

This study shows that the variation of input voltage has a significant effect on the performance of the small Tesla Coil, both in terms of resonant frequency and power transfer efficiency. The measured resonant frequency shows a tendency to approach the theoretical value (48.45 kHz) as the input voltage increases. The maximum deviation of 3.40% occurs at an input voltage of 12V, while the minimum deviation is 0.31% at an input voltage of 24V.

The power transfer efficiency increases significantly from 76.09% at 12V input voltage to 89.65% at 24V input voltage. This efficiency increase is due to the reduction in component losses at higher input voltages. Deviations between theoretical and measured frequencies are caused by component tolerances (capacitance and inductance), power losses in active components (such as transistors), and external noise. Based on the calculation of Quality Factor (Q), inductance ratio, and voltage gain, it is clear that increasing Q and reducing losses in components are the keys to improving circuit performance.

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