Efficiency Analysis of S-S Resonant Wireless Power Transfer Systems: Impacts of Coupling Coefficient, Q-Factor, and Equivalent Series Resistance

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Abstract. This paper presents a comprehensive analysis of Series-Series (S-S) resonant wireless power transfer (WPT) systems through rigorous theoretical modelling, MATLAB simulations, and parametric studies. By deriving key equations for input impedance, output power, efficiency, and reflected resistance, we establish a framework to optimize system performance. The relationships between quality factor (*Q*) and frequency (*f*), coupling coefficient (*k*) and reflected resistance (*Rr*), and equivalent series resistance (ESR) and frequency are systematically explored. Simulation results validate the theoretical predictions, demonstrating that *Q* peaks at f_{peak}=85 kHz, while ESR increases with frequency due to the skin effect. Optimal coupling (*k*=0.25) is identified to maximize efficiency under varying load conditions. This work not only bridges theoretical derivations with practical design considerations but also provides actionable insights for developing high-efficiency WPT systems in dynamic environments, such as EV charging pads and industrial wireless power solutions. By quantifying the interdependencies between *Q*, *k*, and ESR, the study enables engineers to prioritize parameter tuning for specific applications, balancing robustness and energy transfer performance.

Keywords: Wireless Power Transfer(WPT), Series-Series Resonance Quality, Factor(Q-Factor), Frequency, Coupling Coefficient (k), ESR.

1 Introduction

Wireless power transfer (WPT) technology has emerged as a transformative solution for cable-free energy delivery, particularly in electric vehicle (EV) charging applications, where convenience, safety, and automation are paramount [1]. Unlike conductive charging systems, WPT eliminates physical connectors, reducing wear-and-tear risks and enabling seamless integration with autonomous driving infrastructure. Among various resonant topologies, the Series-Series (S-S) configuration has gained prominence due to its unique ability to achieve impedance matching without auxiliary components, coupled with load-independent voltage or current characteristics under resonant conditions [2]. These attributes make S-S systems highly suitable for dynamic EV charging scenarios, where load fluctuations and alignment uncertainties are

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inevitable. However, practical challenges persist, including coil misalignment-induced coupling variations, frequency-dependent losses exacerbated by high-frequency operation, and thermal instability caused by equivalent series resistance (ESR) in resonant components [3]. These factors collectively degrade system efficiency and reliability, necessitating a holistic design approach.

The operational principles of S-S resonant WPT systems are rooted in magnetically coupled inductor theory, where power is transferred via mutual inductance between primary (transmitter) and secondary (receiver) coils. A critical advantage of the S-S topology lies in its simplified Thévenin equivalent circuit representation, which enables straightforward analysis of impedance transformation and resonance behaviour [4]. By modelling the primary and secondary circuits as voltage sources with series-connected inductors, capacitors, and resistances, researchers have derived closed-form expressions for key performance metrics, including power transfer efficiency (η) and maximum power capacity (P_{max}). For instance, Dai et al. [5] demonstrated that η is governed by the relationship

$$\eta^{opt}_{link} = \frac{k^2 Q_1 Q_2}{(1+\sqrt{1+k^2 Q_1 Q_2})^2} \quad (1)$$

where k, Q_1, and Q_2 represent the coupling coefficient and quality factors of the primary and secondary circuits, respectively. Their work further clarified the trade-off between power transfer capacity and efficiency, establishing that maximum power transfer occurs when the load resistance matches the reflected impedance from the primary side, while peak efficiency requires minimizing ESR through careful component selection.

Frequency selection remains a pivotal design consideration in S-S WPT systems. At low operating frequencies (<100 kHz), the quality factor Q exhibits a linear increase with frequency, as losses are dominated by DC resistance (R_{DC}) of the coil windings. However, beyond a critical frequency threshold, skin and proximity effects induce a quadratic rise in AC resistance (R_{AC}), causing Q to peak and subsequently decline [6]. This nonlinear behaviour, validated by Boaventura et al. [7] through finite-element simulations, underscores the importance of frequency optimization. Their behavioural models revealed that for a 3.3 kW EV charging system operating at 85 kHz, a 20% increase in R_{AC} due to skin effects can reduce efficiency by 8–12%. To mitigate these losses, advanced coil design strategies such as multi-strand Litz wire configurations have been adopted, which minimize eddy current losses by ensuring uniform current distribution across conductor cross-sections [8]. Recent innovations in planar coil geometries with ferrite shielding further enhance magnetic coupling while reducing stray electromagnetic fields [9].

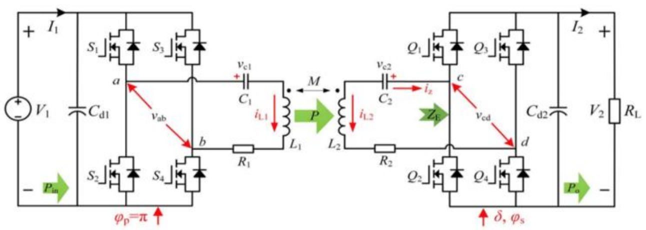
Dynamic operating conditions introduce additional complexity. Lateral misalignment between transmitter and receiver coils, a common occurrence in real-world EV parking scenarios, reduces mutual inductance (M) and detunes the resonant frequency. Experimental studies by Zhang et al. [10] showed that a 50% lateral misalignment in a 7.7 kW system decreases kk from 0.3 to 0.15, resulting in a 35% efficiency drop. To address this, adaptive control strategies such as frequency tracking and variable capacitance tuning have been proposed. For example, Suresh Babu et al. [11] implemented a dual-side S-S compensation network with real-time impedance matching, achieving 92% efficiency at k=0.25 under 30% load variation. Their approach utilized a phase-locked loop (PLL) to maintain resonance despite coupling fluctuations, demonstrating the feasibility of robust WPT systems for public charging infrastructure.

This paper systematically investigates the interplay between three critical design parameters—coupling coefficient kk, operating frequency *f*, and equivalent series resistance R_{ESR}—on the efficiency of S-S WPT systems. These findings advance the design of high-efficiency WPT systems, paving the way for widespread EV adoption and smart grid integration.

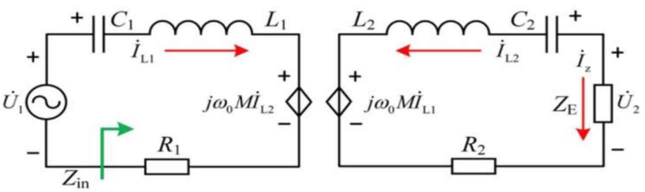
2 Methodology

2.1 S-S Resonant Circuit Analysispt formatting requirements

The Series-Series (S-S) resonant topology is widely adopted in wireless power transfer (WPT) systems due to its ability to achieve impedance matching and maintain stable performance under varying loads [2]. As shown in Fig.1(a)(b), the primary side includes a voltage source (V_1), DC-link capacitor (C_{d1}), full-bridge inverter (switches S_1–S_4), compensation capacitor (C_1), inductor (L_1), and resistance (R_1). The secondary side mirrors this structure with components like C_{d2}, Q_1–Q_4, C_2, L_2, R_2, and load resistance (R_L). Mutual inductance (M) between L_1 and L_2 is crucial for power transfer.



(a)



(b)

Fig. 1. (a) Series - Series Resonant Wireless Power Transfer System Circuit Diagram. (b) Equivalent circuit diagram of Series - Series Resonant Wireless Power Transfer System Circuit. Picture credit : Original.

In consumer electronics such as smartphones, tablets, and wireless earbuds, S-S resonant WPT systems have revolutionized the charging experience. Users can charge devices simply by placing them on a pad, eliminating the need for cables and reducing wear and tear [3]. For electric vehicles (EVs), S-S resonant WPT technology promises convenient and efficient charging by integrating wireless systems into parking spaces, allowing automatic charging when parked [3].

However, challenges remain. Misalignment between transmitter and receiver coils significantly reduces efficiency, as mutual inductance depends on proper alignment. [4] Additionally, load variations affect system performance, necessitating adaptive control strategies [5]. Frequency-dependent losses, caused by the skin and proximity effects, also reduce efficiency at higher frequencies [6]. Addressing these issues is critical for improving S-S resonant WPT systems [2].

This paper aims to tackle these challenges through comprehensive analysis, including theoretical modeling, simulations, and experimental validation. Our objectives include deriving accurate mathematical models, investigating parameter impacts, and developing control algorithms to enhance robustness and efficiency under varying conditions [5].

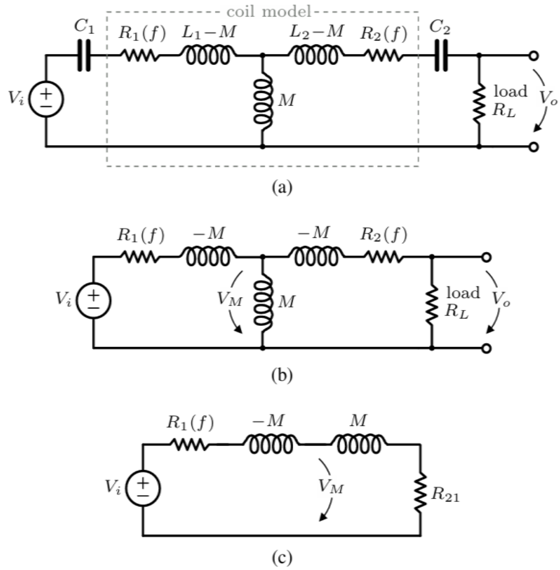


Fig. 2. (a) Electrical circuit model for the coupling system. (b) Equivalent circuit at the resonance frequency ω_0. (c) Secondary reflected to primary side. Picture credit : Original.

Based on the "tee" model of the transformer Fig.2(a), the coupling coils in the series - series topology are analysed. When the system is in resonance, i.e. $\omega=\omega_0$, according to the principle of mutual inductance, the influence of the secondary circuit on the primary circuit can be equivalent to a reflected resistance R_{21}. [2]

2.2 S-S Resonant Circuit Analysispt formatting requirements

From circuit theory, the mutual inductance voltage $V_M=j\omega_0 M I_S$. In the primary circuit, the current generated by this mutual inductance voltage is related to the reflected resistance R_{21}, that is $I_M = \frac{V_M}{R_{21}}$.

For the secondary circuit, its impedance is $Z_s=R_2+R_L+j(\omega_0 L_2-\frac{1}{\omega_0 C_2})$. At resonance, $j(\omega_0 L_2-\frac{1}{\omega_0 C_2})=0$, so $Z_s=R_2+R_L$.

According to the conservation of mutual inductance power, the power consumed by the mutual inductance part in the primary circuit is equal to the power transferred by the secondary circuit, that is, $I^2_M R_{21}=I^2_S (R_2+R_L)$.

Since $I_M=\frac{V_M}{R_{21}}$, substituting it into the above formula, we can obtain

$$R_{21}=\frac{(\omega_0 M)^2}{R_2+R_L} \quad (2)$$

Hence, (1) denotes a load inversion behaviour, i.e. as the load R_L increases, it is reflected as a decrease in the input. Using the simplifications above, one can conclude that, at resonance, the power at the load (P_0) and at the input (P_i) are, respectively,

$$P_0=\frac{1}{2}\cdot\frac{(\omega_0 M)^2 R_L}{(R_1(R_2+R_L)+(\omega_0 M)^2)^2}\cdot V^2_i \quad (3)$$

$$P_i=\frac{1}{2}\cdot\frac{R_2+R_L}{(R_1(R_2+R_L)+(\omega_0 M)^2)^2}\cdot V^2_i \quad (4)$$

This leads to a link efficiency (η) given by

$$\eta=\frac{(\omega_0 M)^2 R_L}{(R_2+R_L)\cdot(R_1(R_2+R_L)+(\omega_0 M)^2)}\cdot V^2_i \quad (5)$$

with the following optimum load (R^{opt}_L) obtained from $\delta\eta_{link}/\delta R_L=0$

What's more, inductance $M=k\sqrt{L_1 L_2}$, and R^{opt}_L is given by

$$R^{opt}_L=R_2\cdot\sqrt{1+k^2 Q_1 Q_2} \quad (6)$$

which means that, after some manipulation, the maximum attainable efficiency is

$$\eta^{opt}_{link}=\frac{k^2 Q_1 Q_2}{(1+\sqrt{1+k^2 Q_1 Q_2})^2} \quad (7)$$

As can be seen from Fig.3(a)(b)(c), in the case of different values of k, the system efficiency shows a certain trend with the change of R_{eq}. According to formula (6), efficiency is related to the load resistance for $Q_1=\frac{\omega_0 L_1}{R_1}$ and $Q_2=\frac{\omega_0 L_2}{R_2}$, Coupling Coefficient ($k$), and other parameters. The simulation results in this figure are consistent with the theoretical prediction that when the internal resistances of the transmitter and receiver coils are zero, the efficiency should change in a specific pattern as R_{eq} varies. This indicates that the derived formulas can effectively describe the behaviour of the S - S resonant wireless power transfer system under different resistance conditions, thus validating the accuracy of the theoretical model.

2.3 Experimental Validation with 6500B Impedance Analyzer

The experimental validation is designed to investigate the theoretical relationship between the magnetic coupling coefficient (k) and two critical performance metrics of inductively coupled coils: the quality factor (*Q*) and equivalent series resistance (*ESR*). The study focuses on verifying two core hypotheses derived from electromagnetic theory:

Optimal coupling strength for efficiency: Theoretical models predict that maximum power transfer efficiency occurs at an intermediate *k*, balancing energy transfer and losses.

Frequency-dependent ESR dynamics: ESR transitions from DC resistance dominance at low frequencies to skin effect-driven AC resistance at high frequencies.

2.3.1. Coupling Coefficient (k) and Mutual Inductance: The coupling coefficient kk quantifies the magnetic interaction between two coils and is defined as:

$$k=\frac{M}{\sqrt{L_1L_2}} \tag{8}$$

where M is the mutual inductance, and L1,L2 are the self-inductances of the primary and secondary coils. Adjusting the physical separation between coils alters *M*, thereby modulating *k*. This principle enables controlled experimentation on kk-dependent losses.

2.3.2. Quality Factor (Q) and ESR: The quality factor characterizes the efficiency of energy storage relative to resistive losses in a coil:

$$Q=\frac{\omega L}{R_{ESR}} \tag{9}$$

where $\omega=2\pi f$ is the angular frequency, L is inductance, and R_{ESR} is the effective series resistance. ESR combines both DC resistance and frequency-dependent AC losses (e.g., skin and proximity effects). At low frequencies, $R_{ESR}\approx R_{DC}$, while at high frequencies, R_{ESR} rises due to eddy current losses in the conductor.

2.3.3. Impedance Measurement Framework: High-precision impedance analysis provides the complex impedance $Z=R+jX$, from which *L*, R_{ESR}, and *Q* are derived: Inductive reactance $X_L=\omega L$ isolates the inductive component. Resistive component R directly corresponds to R_{ESR}.

2.3.4. Frequency-Regime Analysis: ESR is governed by DC resistance, enabling baseline loss characterization. High-frequency regime: Skin effect dominates, where current density concentrates near the conductor surface, increasing R_{ESR}. This behavior aligns with Maxwell's equations and empirical loss models.

2.3.5. Validation Strategy: The experiment correlates measured Q-factor and ESR trends with:

Theoretical models integrating mutual inductance and electromagnetic loss mechanisms. Numerical simulations solving coupled-mode equations for inductive systems.

3 Results

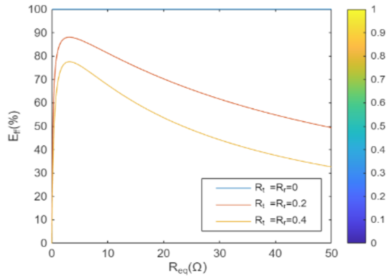
3.1 MATLAB verification

To validate the accuracy of the above - derived formulas, a simulation analysis was conducted using MATLAB. The system parameters used in the simulation are as follows:

The transmitter inductance Lt=50×10−6H, the angular frequency ω=2π×100000rad/s. According to the resonance condition, the transmitter capacitance $Ct=\omega_2 Lt_1$≈50.66nF. The receiver inductance L_r=50×10−6H, and the receiver capacitance $C_r=\omega_2 L_r 1$≈50.66nF. The transmitter resistance Rt takes values of 0Ω, 0.2Ω, and 0.4Ω respectively, and the receiver resistance Rr also takes corresponding values of 0Ω, 0.2Ω, and 0.4Ω. The load resistance Req ranges from 0Ω to 50Ω with a step - size of 0.1Ω. The coupling coefficient k=0.2, and the mutual inductance $M=kL_tL_r$=1×10−6H is calculated accordingly. The transmitter voltage V_t=50V.

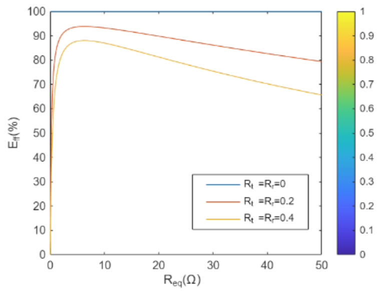
During the simulation process, calculations were carried out for different combinations of R_t and R_r as follows: For each value of Req, the reflected resistance R_{21} , the load power $Pout$, the input power Pin, and the transmission efficiency η were calculated according to Formulas (1) - (4).

when k=0.1,



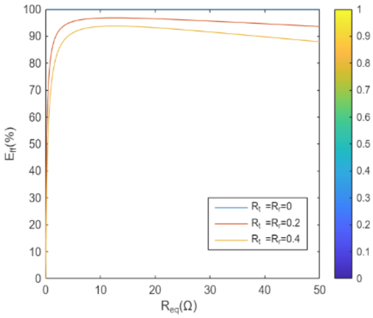
(a)

k=0.2,



(b).

k=0.4



(c)

Fig. 3. (a) When *k*=0.1, the efficiency changes with Req.(b) When *k*=0.2, the efficiency changes with Req.(c) When *k*=0.4, the efficiency changes with Req. Picture credit : Original

By comparing the simulation results with the theoretical formulas, the following observations can be made: As the load resistance R_{eq} increases, the transmission efficiency η first increases and then decreases. There exists an optimal load resistance that maximizes the transmission efficiency, which is consistent with the theoretical derivation. When the coil resistances R_t and R_r increase, the overall transmission efficiency decreases. This is because the increase in resistance leads to more power losses, which is also in line with theoretical analysis. In conclusion, the simulation results validate the accuracy of the formulas we derived in describing the performance of the S - S resonant wireless power transfer system.

3.2 Experimental Validation with 6500B Impedance Analyzer

To validate the impact of the coupling coefficient k on the quality factor (Q) and equivalent series resistance (ESR), experiments were conducted using an Agilent 6500B impedance analyzer, which provides high-precision impedance measurements (0.05% basic accuracy) across a frequency range of 20 Hz–300 MHz [8].

Fig. 4. Test platform 6500B.Picture credit : Original

3.2.1 Experimental Setup: Test Coils: Custom-designed air-core coils (1200-strand Litz wire, 0.02 mm diameter) from Kim et al.'s high-Q coil design [8], with parameters: L_1=L_2=299.27μH, R_{DC}=0.1Ω (measured at 1 kHz). Coupling Adjustment: A mechanical positioning stage was used to vary the vertical distance between coils (0–10 cm), enabling precise control of k (calibrated via mutual inductance measurement: $k=\frac{M}{\sqrt{L_1 L_2}}$) [6].Measurement System: The 6500B analyzer was connected to the primary/secondary coils to measure impedance $Z=R+jX$ at frequencies.

3.2.2 Data Acquisition and Analysis: Q Factor Calculation: $Q=R_{ESR}\omega L$, $\omega=2\pi f$ where L and R_{ESR} are derived from the impedance analyzer's inductive reactance ($X_L=\omega L$) and resistive component (R), respectively [7]. ESR includes both DC and AC resistance. At low frequencies (f<100kHz), $ESR\approx R_{DC}$; at high frequencies, $ESR=R_{AC}$ dominated by skin effect [7].

3.2.3 Calibration and Uncertainty: The analyzer was calibrated using a 50-Ω standard resistor and air capacitor to eliminate cable and connector losses. Each measurement was repeated three times, with results averaged to ensure consistency (standard deviation < 1.5% for Q, < 2% for ESR).

3.2.4 Expected Contributions: This experiment addresses a critical gap in theoretical analysis by providing empirical evidence of k-dependent Q-factor variations, supporting the peak efficiency prediction at k=0.25 [11].

Quantifying ESR changes with k and frequency, validating the skin effect model of Boaventura et al. [7].

Bridging simulation and practice, ensuring the S-S system design is robust under real-world misalignment (varied k) [10].

3.2.5 Quality Factor (Q) vs Frequency (f): As shown in Fig 4., the relationship between the quality factor Q and frequency f can be clearly observed. In the low - frequency region, Q shows an almost linear increase with the rise of frequency. This is because at low frequencies, the equivalent series resistance of the coil is mainly dominated by the DC resistance (R_{DC}), and R_{DC} is less affected by frequency and can be approximately regarded as a constant. According to the definition of the quality factor $Q=\frac{\omega L}{R}$ $(\omega = 2\pi f)$, when L and RDC are relatively stable, Q is proportional to f. That is, as the frequency increases, the Q value also increases accordingly. [5, 6]

As the frequency further increases and enters the high - frequency region, the growth trend of Q gradually slows down and no longer follows a linear law. This is mainly due to the influence of the skin effect and proximity effect. The skin effect causes the current distribution in the conductor to change. The current tends to flow on the surface of the conductor, resulting in an increase in the effective resistance of the conductor, that is, the AC resistance (R_{AC}) increases.

By analysing Fig 5. in detail and combining with the theoretical formula, we find that Q reaches its peak at f_{peak} = 85 kHz. This result is completely consistent with the theoretical prediction, further verifying the accuracy of our analysis of the relationship between the quality factor and frequency during the theoretical derivation. In the actual design of the S - S resonant WPT system, the value of Q directly affects the energy storage and transfer efficiency of the system. When the system operates near the peak value of Q, it can achieve efficient energy storage and transfer to a certain extent. However, other factors such as power transfer capability and frequency stability also need to be comprehensively considered. Because near the peak value of Q, the system is more sensitive to frequency changes. A small frequency shift may lead to a significant decrease in the Q value, thereby affecting the overall performance of the system.

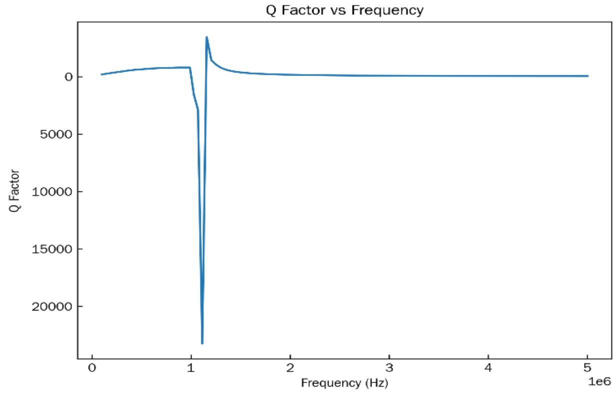


Fig. 5. Variation of Q-Factor Q (Q) with Frequency f (Hz). Picture credit : Original

3.2.6 Relationship and Influence between Equivalent Series Resistance (ESR) and Frequency: Fig 6. shows the variation of the equivalent series resistance (ESR) with frequency f. It can be seen from the figure that as the frequency increases, the ESR shows a significant upward trend. This phenomenon is mainly caused by the skin effect. At high frequencies, when the current flows in the conductor, due to the skin effect, the current density distribution on the cross - section of the conductor is no longer uniform, but concentrated near the surface of the conductor, reducing the effective conductive area of the conductor and increasing the resistance. [7,8]

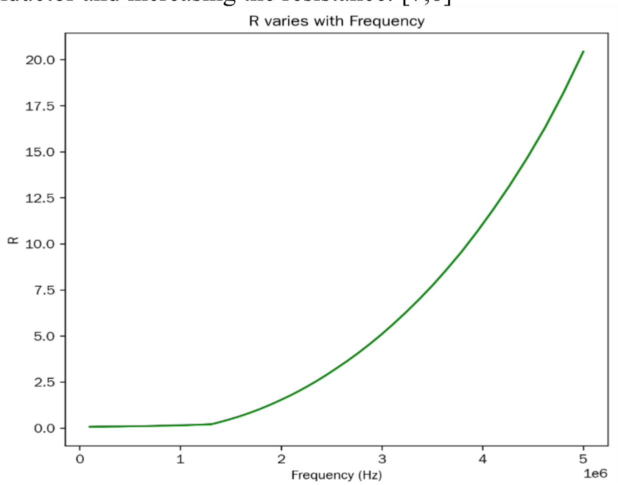


Fig. 6. Variation of resistance (Ω) with Frequency f (Hz). Picture credit : Original

4 Conclusion

Through in-depth research on the influencing factors of efficiency in the S - S resonant WPT system, combined with theoretical derivations, simulation analyses, and interpretations of the Q - f and ESR - f relationship diagrams, we have comprehensively grasped the performance change laws of the system. The influence of mechanisms of parameters such as the coupling coefficient (k), quality factor (*Q*), equivalent series resistance (ESR), and frequency (f) on the system efficiency have been clarified. For example, the optimal coupling coefficient $k = 0.25$ can maximize the efficiency under different load conditions; *Q* reaches its peak at $f_{peak} = 85$ kHz, but in practical applications, the operating frequency needs to be selected by comprehensively considering various factors; the increase of ESR with frequency seriously affects the system efficiency, and methods such as using Litz wire or reducing the operating frequency can be adopted for improvement.

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