Experimental Comparison of Designed Inductance Coils for Wireless Power Transfer

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Abstract – The paper is devoted to the comparison of different types and different values of coils for inductive power transfer in the classical circuit. This topic is relevant with the growing demand and interest in wireless chargers and the diversity of inductance coils for wireless power transfer. The main geometric parameters affecting the coil efficiency are determined. For experimental verification the classical scheme for wireless power transfer is used based on a full-bridge inverter. Different coils at different distance between them, lateral misalignment and load resistance changed are tested. It is determined that single-layer coils have better transmit-receive efficiency than double-layer ones, especially with series-series compensation topology. The application of two-layer coils is recommended in case of high input current. The investigated samples have efficiency at the level of industrial standards. The design approach can be used for any level of power and application, including wireless charging of electric vehicle batteries.

Keywords – AC-DC power converters electromagnetic coupling; Finite element modelling; Inductive power transmission; Wireless power transfer.

I. INTRODUCTION

The electromagnetic system is a very important part of Wireless Power Transfer (WPT) devices, and it makes a major contribution to the efficiency of the entire system. The electromagnetic system consists of transmitter and receiver coils that are separated by a non-magnetic gap.

The overall efficiency of the WPT device and the efficiency of energy transmission and receiving are determined by the ratios of different geometric parameters [1]–[3]. In addition to the geometric parameters of the coil, efficiency is also determined by its design, namely, the number of layers, the cross-section of wires, etc. The efficiency of inductors, connected through a non-magnetic interval, is mainly determined by the product of the magnetic coupling coefficient \( k \) and the quality factor \( Q \) [1].

The inner and outer radii of the circular coil mainly determine the coupling coefficient [1], [2]. For a given outer radius, a smaller inner radius always leads to an increase in magnetic coupling. However, when the inner radius reaches about half the outer radius, an additional increase in the coupling coefficient becomes insignificant [2]. The wire diameter and the distance between the turns do not have a significant effect on the coupling factor. The optimization calculations in [2] also determined that the number of the primary turns and the ratio of the number of the primary turns to that of the secondary turns also have a slight influence on the coupling coefficient. On the other hand, increasing the number of turns and placing the winding in one layer increases the coupling between the coils of the primary and secondary coils, which increases the quality factor and the coupling coefficient [3].

The coil inductance is directly proportional to the square of the number of turns. The coil resistance is directly proportional to the number of turns. An increase in the number of turns leads to an increase in the inductance and quality factor, while the active resistance increases less intensively [3]. A balance must be found between the wire diameter and the number of turns to obtain optimum inductance.

The active resistance (ESR) of the coil due to the skin effect at high frequencies may differ from the active resistance with only DC current. To reduce the active resistance of the alternating current, a litz wire is used [1], [4].

In addition, it should be noted that in order to implement an efficient WPT system, it is necessary to use the reactive power compensation caused by the presence of inductance [5]. According to sources, the efficiency of WPT without compensation does not exceed 50% [6].

The main aim of the article is to investigate and compare coils with different inductance as part of WPT system at different reactive power compensation schemes.

II. CASE STUDY: SYSTEM DESCRIPTION

The research of the classical WPT scheme [7], [8] is presented for different coil types and compensation topologies (Fig. 1). The primary (transmitting) part of classical WPT scheme consists of a full-bridge inverter, a primary series
compensation capacitor $C_{\text{prim}}$ and an inductance $L_{\text{prim}}$. A secondary (receiving) part contains a secondary series $C_{\text{sec-ser}}$ or a parallel $C_{\text{sec-par}}$ compensation capacitor and an inductance $L_{\text{sec}}$, a passive diode bridge rectifier, an output filter $C_T$ and a load resistance $R_L$. Experimental tests were conducted in open-loop mode at a frequency of 100 kHz.

There are several options for implementing reactive power compensation in a WPT system [5], [9]. The difference is a series or parallel placing of the capacitor relative to the inductor. In all circuits, the capacitor is calculated so that the switching frequency of the transistors is close to the resonance frequency of the LC link. There are four basic compensation topologies on the basis of which the vast majority of semiconductor structures are built: series-series (SS), series-parallel (SP), parallel-serial (PS) and parallel-parallel (PP). Analysing the application of existing topologies, it was found that the most common were serial-serial and serial-parallel topology [2], [5], [9]–[11].

![Fig. 1. Classical WPT circuit.](image)

Due to the complexity of analytical calculations [12], the mathematical package “ANSYS Electromagnetics Suite” was used to determine the parameters of the inductors and the phenomenon of mutual induction [13]. The calculations were performed using the Finite Element Modelling method (FEM) [14].

## III. RESULTS OF EXPERIMENTS AND SIMULATIONS

A vast majority of commercial wireless solutions have a power less than 20 watts. In most cases of such solutions, the intermediate step-down transformer is utilised. Otherwise, a much larger self-inductance of the coil is required on the transmitting side [2]. Devices with higher power levels are at the stage of research and commercialization.

In the previous paper [15], different types of inductors for wireless power transmission were analysed. As a result, the shape of circular coils was chosen. Previous simulation results of the whole WPT system operation with such inductances were carried out in the PSIM Simulation program and covered in previous work [15]. The experiment was conducted with handmade circular coils of 65 µH and 10 µH (Fig. 2c). Also, for experimental comparison, the previously developed and modelled inductors were taken with inductance 5.8 µH, 65 µH, 10 µH (Table I). Each coil is mounted on a ferrite plate, which increases the coupling coefficient k between the coils and shields their electromagnetic field outside the working space. All coils have similar geometric dimensions. Different inductance value is realized due to the different number of turns and the diameter of the wire. The first coil (5.8 µH) has a double wire winding, which is enclosed in two layers: one above the other as shown in Fig. 2c. Double coils of wire are connected in parallel at each of the terminals of the coil. Coil parameter simulation and experimental inductance testing were performed at 100 kHz.

### TABLE I

| Description of parameter | Nominal parameters for coil |
|--------------------------|-----------------------------|
| Inductance value         | 5.8 µH, 10 µH, 65 µH        |
| Outer diameter of coil, mm| 50, 51, 52                  |
| Inner diameter of coil, mm| 20                          |
| Wire diameter, mm        | 1.4, 1.2, 0.48              |
| Length and width of the ferrite core with height, mm | 53 x 53 x 2.5 |
| Structure of layers      | double, single, single      |
| Relative magnetic permeability of ferrite | 650 |
| Number of turns          | 10 (double), 12, 30          |
| Coil resistance, Ω       | 0.004, 0.0013, 0.5          |

![Figure 2 shows the experimental WPT system (Fig. 2a), tested coils (Fig. 2b) and a double-layer coil 3D model (Fig. 2c).](image)

The WPT system efficiency was determined without considering the actual power losses in the control system. The output power was displayed on the electronic load screen. Input power was determined by measuring the input voltage and current with multimeters. The temperature of the circuit elements was also measured with a thermal camera. The highest temperature was 64 °C in the transistor driver power circuits at 2.5 A input current.

### A. Experimental and Simulation Dependencies from Load Resistance at Different Input Voltage Levels

Experiment number 1 (exp. 1) was made with two coils 5.8 µH and SS compensation circuit; experiment number 2 (exp. 2) was made with two coils 65 µH and SS compensation; experiment number 3 (exp. 3) was made with transmitter coil 65 µH and receiver 10 µH and SS compensation; experiment number 4 (exp. 4) was made with transmitter coil 65 µH and receiver 10 µH and SP compensation circuit.

Figure 3 shows experimental and simulation dependencies with output power ($P_{\text{out}}$) and efficiency ($E$) from load resistance ($R_{\text{load}}$) at different input voltage levels and gap between coils ($\delta$) $\delta = 1$ mm. Some waveforms for those experiments are shown in Fig. 5.
Results for experiment number 1 are shown in Fig. 3a–b. For each load value, the pulse rate of the inverter was selected to obtain the maximum output power. The graph of power change at $V_{\text{in}} = 10$ V differs from other curves. In Fig. 3a, there is the highest output power. In addition, the highest input voltage corresponds to the best efficiency values for all load points (Fig. 3b). It should be noted that experimental investigations show that for each value of the input voltage there is an optimal value of the load at which the maximum output power and efficiency can be achieved.

For experiment 2 at SS compensation results are shown in Fig. 3c–d. Two 65 $\mu$H coils deliver lower power at higher input voltages than those with less self-inductance coils (Fig. 3c). It can be concluded that the higher the inductance of the coils, the lower the output current and power will be when the output voltage level is increased. As the input voltage decreases, efficiency also decreases (Fig. 3d). However, the absolute values of efficiency are higher than in the previous experiment.

It can be concluded that the use of coils with an inductance of 5.8 $\mu$H is more appropriate at low input voltages and high current. This is embedded in geometry (double coils of wire of sufficiently large diameter with relatively small inductance).

Results for experiment number 3 are shown in Fig. 3e–f. This experiment was performed at SS compensation but with different inductances on the primary and secondary sides (Fig. 3e). The transmitted power is approximately the same value as in the case of exp. 2 (Fig. 3c). However, the receiving coil has an inductance of 10 $\mu$H, and it can accept more power than transmitted in this case. The efficiency is slightly lower (Fig. 3f) than for the case of two 65 $\mu$H coils.

For experiment 4 at SP compensation results are shown in Fig. 3g–j. It is known that in order to work effectively with a SP compensation scheme, it is necessary to adjust the resonant circuit of the transmission part when changing the coupling coefficient $k$ between the receiving and transmitting coils [9]. Analytically this will be defined as follows:

$$C_{\text{prim}} = \frac{1}{L_{\text{prim}}(1-k^2) \omega_{\text{res}}^2}.$$  

According to the previous experiments, the dependences of the output power and the efficiency as a function of the load are shown in Fig. 3g and Fig. 3h. The receiving coil has an inductance of 10 $\mu$H, the transmitting coil is 65 $\mu$H. Unlike SS compensation, maximum power is achieved with relatively low load resistance. All values are obtained at the maximum achievable coupling coefficient $k = 0.95$.

Fig. 3i and Fig. 3j show similar results, but with different values of the coupling coefficient. It can be seen that at $k = 0.8$, both maximum power and efficiency are significantly reduced.
It should be noted that the decrease in efficiency and power occurs despite the fact that the capacity in the transmission circuit also changes in accordance with Eq. (1). These results were confirmed by the simulation results.
Fig. 3. Experimental and simulation dependences with output power (on the left) and efficiency (on the right) from load resistance \( R_{\text{load}} \) at different input voltage levels and at gap between coils \( \delta = 1 \text{mm} \) for the investigated compensations of topology.

Fig. 4. Simulation and experimental dependences of efficiency and output power from changing the air gap (b, c, e) and lateral misalignment (a, d, f) between coils.
B. Experimental and Simulation Dependences from Changing the Air Gap and Lateral Misalignment between Coils

A series of follow-up experiments was conducted to investigate the effect of the coupling coefficient on the performance of the WPT in more detail. Figure 4 shows simulation and experimental dependences efficiency and output power from changing the air gap (δ) and lateral misalignment (Δ) between coils. For experiments \(V_{in} = 30 \, V\) (for Fig. 4a–b, \(V_{in} = 5 \, V\)), \(δ = 1 \, mm\). Diagrams are shown for optimum point for each experiment. For experiment 1 this is 10 \(Ω\) (Fig. 4a–b); for exp. 2 \(R_{load} = 65 \, Ω\) (Fig. 4c–d); for exp. 4 (SP compensation) \(R_{load} = 18 \, Ω\) (last two diagrams).

To compare the experimental curve of the coupling coefficient depending on the distance between the coils with the simulation data, the coupling coefficient was determined. According to the known method, coils are fixed at a certain distance. The self-inductances (\(L_1\) and \(L_2\)) and the inductance of the series connected coils are measured (\(L_{12}\)). As a result, the following value of the mutual inductance \(M\) is calculated by (2):

\[
M = \frac{1}{2}(L_{12} - L_1 - L_2) . \tag{2}
\]

According to the known Eq. (3) [16], the coupling coefficient can be determined:

\[
k = \frac{M}{\sqrt{L_1 \cdot L_2}} . \tag{3}
\]

In the first experiment (exp. 1), the high coupling coefficient was observed due to the short distance. With increasing distance there was a decrease in the coupling coefficient (Fig. 4b). The results of simulation and experiment are almost identical, which indicates the correctness of the coil model.

According to the SS topology properties, the efficiency of energy transfer at changing distance between the coils over a wide range is acceptable and is kept at a relatively high level (Fig. 4c–d). The point of approaching the curves to zero in Fig. 4d for experiment 2 indicates that 50 % of the secondary coil overlap is reached. With further misalignment, energy begins to transfer again in small quantities due to the interaction between the outer diameters of the primary and secondary coils.

Theoretically, the maximum power and efficiency for SP compensation at \(k \approx 0.95\) coupling is expected at zero misalignment, since the capacitor is calculated for this value. However, the maximum was observed at the distance of 3–4 mm air gap (Fig. 4e–f). For other couplings, the behaviour of the curves according to the theory is as follows: if the capacitors are designed for weaker coupling, then the distance at which the maximum output power and efficiency are reached will be greater. This deviation can be explained by the difference in the outer diameters of the coils (up to 1–2 mm) and some displacement of the coils from the centre of ferrite for the handmade coils.

**Fig. 5.** Waveforms at a distance of 1 mm between coils: a) output voltage of the inverter \((V_{inv})\) and the current on the primary side \((I_{prim})\); b, c) voltage \((V_{sec})\) and the current on the secondary side \((I_{sec})\) (after the secondary capacitor before the diode bridge).
The relatively low efficiency of the coil of 5.8 µH in the experiments can be explained by a lower coupling coefficient \( k = 0.85 \) for an air gap of 1 mm compared to the other coils under investigations. This fact is confirmed by modelling and experimental measurement of mutual inductances with next calculation. This is also confirmation that single-layer coils are more efficient than double-layer coils. In the case of a single-layer coil, all coils are in the same plane, which increases the coupling coefficient between such coils. In double-layer coil, all coils are in the same plane, which increases losses. Therefore, the coil efficiency will be less. It is also worth noting partially the quality factor are reduced (due to fewer turns).

At the same time, the coupling coefficient and active resistance. At the same time, the coupling coefficient and load changes due to SS topology properties. High efficiency and transmit power are achieved by SP compensation for certain coupling factors for which the primary compensating capacitor is calculated. Therefore, SP compensation can be successfully used at a fixed distance between coils at low load resistance.

The results of investigation can be also generalized to any power level, in particular wireless battery charging systems. At higher power levels, the size of coils is increasing correspondently in order to provide acceptable conduction losses and coupling coefficient.

**ACKNOWLEDGMENT**

The present research has been supported by the Ukrainian Ministry of Education and Science (Grants No. 0117U007260 and No. 0118U003865) and Ukrainian-Latvian project (Grant No. 0119U102105).

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inductors. Table II summarises the main points of study of different coils at different compensation topologies.

**TABLE II**

| Parameters                              | Values                           |
|-----------------------------------------|----------------------------------|
| Number of experiment                    | Exp. 1 Exp. 2 Exp. 3 Exp. 4     |
| Type of compensation                    | SS SS SS SP                      |
| Pair of coils                           | Two 5.8 µH Two 65 µH 65 µH and 10 µH | 65 µH and 10 µH |
| Maximum efficiency                      | 68 % 88 % 85 % 74 %              |
| Maximum achieved output power at load variable, W | 14.5 (at \( V_a = 7V \)) 12 (at \( V_a = 30V \)) 10.4 (at \( V_a = 30V \)) 25 (at \( V_a = 30V \)) |
| Optimum point at load resistance, Ohm    | 10 65 25 18                      |
| Coupling coefficient at air gap 1 mm    | 0.85 Not measured 0.95 0.95      |

The complex research has been conducted, namely, a combination of modelling and experimentation on WPT. As a result, the efficiency of energy transfer at different values of inductance and compensation schemes was determined. More than 80 % energy transfer efficiency was achieved. This is the level of industrial samples.

All inductors had similar geometric dimensions. In this case, double-layer coils have some advantages and are recommended for use in the case of relatively high currents and low voltages. However, in most cases, they will be less efficient than single-layer coils. This is because the decrease in active resistance does not compensate for the significant decrease in the inductance and the coupling coefficient between such coils.

Single coils with different inductance values will be more effective with SS compensation, higher input voltage and less current (higher output load resistance). Two identical 65 µH inductors provide high efficiency over a wide range of coupling and load changes due to SS topology properties. High efficiency and transmit power are achieved by SP compensation for certain coupling factors for which the primary compensating capacitor is calculated. Therefore, SP compensation can be successfully used at a fixed distance between coils at low load resistance.
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