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Ramazan Cetin  
Suleyman Demirel University

Ali Agcal  
Suleyman Demirel University

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A New Method for Calculating the Inductance of Planar Spiral Square Coils Used in Wireless Power Transfer

Ramazan Cetin¹, Ali Agcal¹
¹Department of Electrical and Electronics Engineering, Suleyman Demirel University, Isparta, Turkey
cetinramazan306@gmail.com, aliagcal@sdu.edu.tr
Corresponding Author: cetinramazan306@gmail.com

Abstract - The planar spiral square coil (PSC) is one of the most common structures used in wireless power transfer (WPT) applications. In this paper, a new self-inductance calculation method is proposed for PSC. The self-inductance of the coil should be calculable in order to comprehend the interaction between the coil and the WPT system. In this paper, A new self-inductance calculation method for PSC is proposed by using Greenhouse's method of calculating the inductance between the conductors. The proposed new greenhouse method has been tested for various square sizes, spaces between conductors, the number of turns, and conductor widths. Also, the proposed new method was compared with Current sheet method, modified Wheeler method, and Ansys Maxwell 3D simulation results in terms of calculation error rate. The self-inductance calculation error rate of this method was lower than in all other studies and was below 0.4% in all cases.

Keywords Inductance calculation, planar spiral square coil, self-inductance, wireless power transfer

1 Introduction

Systems for wireless power transmission are designed to transport electrical energy without a physical connection from the transmitter to the receiver. WPT system research has become commonplace in many fields. Today, the global WPT systems market is worth $1 billion [1]. WPT systems have found a place in various fields such as electric vehicles, unmanned aerial vehicles, mobile phones, biomedical devices, and underwater vehicles [2]. Inductive power transfer (IPT) is the most commonly used WPT technology in the literature [1]. Coils transfer energy in the inductively coupled WPT system. A time-varying current flowing through the transmitter coil produces a time-varying magnetic field. The magnetic field produced induces a voltage in the receiving coil. Thus, wireless power transfer takes place from the transmitter to the receiver.

The most crucial components of the WPT systems are the design, magnetic coupling, and compensation topology. The efficiency of the system is significantly impacted by the coil's design and material. Conventional copper or high temperature superconducting (HTS) is used as the coil material. HTS is lower resistance and more efficient than cooled copper [3]. Planar spiral [4] and solenoid [3] designs are the coil structures most usually utilized in the WPT literature. The magnetic coupling between the transmitter and receiver of the solenoid coils is lower than the planar spiral coils. A planar spiral coil is generally preferred because of its thinner construction and higher coupling. Planar coils are made in a variety of shapes, including circular [5], square [6], rectangular [7], and more (DD, DDQ) [8, 9].

In order to understand the interaction between the coil and the system, it is crucial to determine the self-inductance. Various studies have been done on inductance calculations in the literature. The formulas for the inductance calculations of the coils are presented in [10]. In [11], simplified expressions are presented for calculating the self and mutual inductances of planar coils, rectangular coils, transmission lines, antennas, and similar structures. Greenhouse proposed the concept of negative common inductance [12]. He provided equations to determine the mutual and self-inductance of planar spiral rectangular coils. He made sample calculations for the equations.

The methods used to calculate PSC's self-inductance in the literature are examined in this research. The literature describes a number of techniques for calculating PSC inductance. In [13], a brand-new, simple, and accurate formula for calculating the inductance of square, hexagonal, octagonal, and circular coils was introduced. They compared their methods of calculation to a few earlier studies that examined inductance. The error rate of their proposed method was less than 5%. A technique for the characterization and optimization of rectangular coils was described by Duan et al. [14]. Calculations for self and common inductance, series resistance, parasitic capacitance, and efficiency were shown in relation to the rectangular coil's geometric parameters. Stojanovic et al. [15] presented expressions for the inductance calculation of the meander inductors. The effects of various geometry parameters on inductance were examined using the software tool with expressions. López-Alcolea et al. [16] proposed an analytical model that provides self-inductance and mutual inductance calculations for planar spiral rectangular coils of equal size and parallel. Both single-layer and double-layer coil designs were investigated. They also considered the possibility of a lateral misalignment.

In this study, a PSC self-inductance calculation method was developed. Greenhouse's method for planar spiral structures was adapted for PSC. The proposed method has been tested for different geometric design parameters such as outer edge length distance between conductors, number of turns, and conductor diameter. In all geometric conditions, the proposed method had a lower error rate than other methods in the literature.

The following is an outline of the remainder of the paper. The novel self-inductance calculation method for PSC is...
described in Section II. The calculation results obtained with MATLAB and the simulation results obtained with ANSYS Maxwell 3D for different situations are presented in Section III. The proposed method was compared with other methods in the literature. Section IV gives the conclusion.

2 Planar Spiral Square Coil

The PSC is obtained by spirally placing multiple turns in a square shape on a plane. The self-inductance of the PSC can be expressed in terms of geometric parameters (number of turns, coil dimensions, conductor diameter, distance between conductors) The PSC is shown in Fig. 1.

![Fig. 1. The planar spiral square coil](image)

In PSC, \( D_{\text{out}} \) is the outer edge length, \( D_{\text{in}} \) is the inner edge length and \( s \) is the distance between the conductors. Units are in meters. Numerous methods have been proposed in the literature to calculate the self-inductance of PSC \[13\]. One of these methods is the one suggested by Wheeler. The modified Wheeler formula for PSC is given by (1).

\[
L_{\text{Whe}} = 2.34 \mu_0 N^2 d_{\text{avg}} + 1.27 \mu_0 N^2 d_{\text{avg}} \left( \ln \left( \frac{D_{\text{out}}}{D_{\text{in}}} \right) + 0.18 \rho + 0.13 \rho^2 \right) \tag{5}
\]

Greenhouse proposed the method of calculating the inductance between conductors \[12\]. In this study, the method proposed by Greenhouse was developed for PSC. In this method, the self-inductance of PSC is calculated by obtaining the self-inductances \((L_i)\), positive mutual inductances \((M_p)\), and negative mutual inductances \((M_n)\) of the conductors in each segment. According to the Greenhouse method, the self-inductance of a PSC coil can be calculated by (6).

\[
L_{\text{Sp}} = L_i + M_p - M_n \tag{6}
\]

In order to simplify the inductance calculation of PSC 4 segments are obtained by separating the edges of the square. The segmented square coil is shown in Fig. 2(a). The conductors in each segment are numbered 1, 2, 3, ..., \(N\) from outside to inside as shown in Fig. 2(b).

![Fig. 2. PSC (a) segment numbering and (b) conductor numbering](image)

\( L_i \) is the sum of the self-inductances of each conductor in each segment. \( L_i \) is expressed by (7) and (8) \[14\].

\[
L_i = 4 \sum_{i=1}^{N} l_i \tag{7}
\]

\[
l_i = \frac{\pi D_i}{2} \left( \ln \left( \frac{D_i}{w} \right) + 0.5 \times \frac{2w}{3l_i} \right) \tag{8}
\]

\( l_i \) is the conductor number. \( L_i \) is the self-inductance of conductor number \(i\). \( l_i \) is the length of conductor number \(i\). There are \(N\) conductors in each segment as shown in Fig. 2(b). For PSC, the \(i\)-numbered conductors in the 4 segments are the same. For this reason, the self-inductance of the conductor number \(i\) in any segment is calculated and multiplied by 4. The conductor length is given in (9).

\[
l_i = D_{\text{out}} - 2(w+s)(i-1) \tag{9}
\]

\( D_{\text{out}} \) is obtained by subtracting conductor thickness \(w\) from \(D_{\text{out}}\).

\( M_p \) is positive mutual inductance. It is the mutual inductance between two conductors with the same current direction. The conductors in each segment contribute to the positive common inductance. \( M_p \) can be expressed by (10).

\[
M_p = 8 \sum_{i=1}^{N} \sum_{j=i+1}^{N} M_{ij} \tag{10}
\]

where \(i\) and \(j\) are the conductor numbers. \( M_{ij} \) is the mutual inductance between conductors \(i\) and \(j\).

The two parallel conductors can be of different sizes and
positions. In these cases, Grover's suggested calculations can be used. When Fig. 2 (b) is examined, 2 cases occur for PSC. In the first case, as shown in Fig. 3, the two conductors are aligned, and their lengths are equal. The mutual inductance for this case is calculated with (11) [15]. In addition, (11) is used in the calculation of the common inductance of other cases.

\[
M(l,d)=\frac{\mu_0}{2\pi} \left[ 1 \times \ln \left( \frac{1}{1+\sqrt{1+\frac{d^2}{l^2}}} \right) \right] \]  

(11)

In the second case, as shown in Fig. 4, the two conductors are aligned, and their lengths are unequal [11]. Where l and m are the long and short side lengths, respectively. d is the distance between parallel conductors. p and q are the length differences of the short conductor from the left and right, respectively, with respect to the long conductor. In Fig. 4, mutual inductance calculation for two parallel conductors of unequal length is given in (12).

\[
M_{lm}=\frac{1}{2} \left( M(m+p, d) + M(m+q, d) \right) - \left( M(p, d) + M(q, d) \right) \]  

(12)

Since negative mutual inductance occurs between different segments, i and j in (17) are the conductor numbers of different segments. For example, when examining the 2nd and 4th segments, when \((i, j)=(2,5)\), the negative mutual inductance calculation is made for the 2nd conductor of the 2nd segment and the 5th conductor of the 4th segment. In the calculation of the mutual inductance of different segments, it is used (13) for conductors with different lengths and (11) for conductors with the same length. Which equation to use is determined by \(i\) and \(j\). \(M_{ij}\) expression with respect to \(i\) and \(j\) is given in (18).

The d, l, m, and p values for \(M_n\) are calculated by (19), (20), (21), and (22), respectively [17].

\[
M_{ij} = \begin{cases} (11), & i = j \\ (13), & i \neq j \end{cases} 
\]

(18)

\[
d_{ij} = D_{out0} - 2(w + s)(|i-j|) 
\]

(19)

\[
l_{ij} = D_{out0} - 2(w + s)(|j-1|) 
\]

(20)

\[
m_{ij} = D_{out0} - 2(w + s)(|j-1|) 
\]

(21)

\[
p_{ij} = |i-j|(w + s) 
\]

(22)

The flow diagram of the self-inductance calculation method for PSC is given in Fig. 5 [17].

### 3 Calculation and Simulation Results

In order to test PSC self-inductance calculation methods and the proposed method, analyses were carried out in various situations. Cases were created for various numbers of turns, outer edge lengths, distances between conductors, and conductor diameters. First of all, an interface with a GUI was designed in the MATLAB program for the calculation of the proposed method and other methods. The designed MATLAB GUI interface is shown in Fig. 6. Coils for various situations are designed in ANSYS® MAXWELL 3D. An example of a coil designed in ANSYS® MAXWELL 3D is shown in Fig. 7.

The results from the two programs were compared. For comparison, the error (\(H_e\)) given in (23) and the absolute error rate (\(s\)) given in Equation (24) is used.

\[
H_e = \frac{100}{L_{Max}} \times \left( \frac{L_{Max} - L_{calculated}}{L_{Max}} \right) 
\]

(23)

\[
s (\%) = \frac{H_e}{L_{calculated}} \times 100 \]  

(24)

where \(L_{Max}\) is the value obtained with MAXWELL 3D and \(L_{calculated}\) is the value of the inductance calculated by MATLAB.

In the tables and figures, \(L_{Max}, L_{Squ}, L_{Whe}, L_{CS}\) are the self-inductances obtained by Maxwell 3D simulation, obtained by the proposed method, obtained by the modified Wheeler formula and obtained by the Current sheet formula, respectively. Length unit is mm for \(D_{out}, S\) and, w. Inductance unit \(\mu H\) for \(L_{Max}, L_{Squ}, L_{Whe}, \) and \(L_{CS}\). Also, \(H_{Squ}, H_{Whe}, \) and \(H_{CS}\) in the charts and figures are errors for the proposed method, the modified Wheeler formula, and the Current sheet formula, respectively. \(E_{Squ}, E_{Whe}, \) and \(E_{CS}\) are the absolute error rates for the proposed method, the modified Wheeler formula, and the Current sheet formula, respectively. Absolute error rate values are given as percent (%).
A. Number of Turns

PSCs with an outer edge length of 500 mm, conductor diameter of 1.78 mm, and distance between conductors of 4 mm were created to examine inductance calculation methods according to various numbers of turns. The results of self-inductance, error, and absolute error rate obtained by calculation and simulation are shown in Table 1.

The self-inductance values for various numbers of turns are shown in Fig. 8. Absolute error rates according to various numbers are shown in Fig. 9. When the figures and table are examined, the self-inductance values increase as the number of turns in PSC increases. For the modified Wheeler formula, the error occurred between 1 µH and 8.7 µH, and the absolute error rate was between 0.3% and 18.2%. For the Current sheet formula, the error occurred between 0.5 µH and 2.9 µH, and the absolute error rate was between 0.45% and 3.5%. The modified Wheeler and Current sheet formulas have a high error rate at the low number of turns. It has a relatively less error rate at the high number of turns. For the proposed method, the error occurred between 0.005 µH and 0.5 µH, and the absolute error rate was between 0.03% and 0.15%. In the self-inductance calculation of the proposed method, it gave better results for various numbers of turn than other methods. The error was 0.5 µH below and the absolute error rate was 0.15% below.

B. Outer Edge Length

In order to examine the inductance calculations according to the various outer edge lengths, PSCs were designed by keeping the other variables constant. PSCs with a number of turns of 10, conductor diameter of 1.78 mm, and distance between conductors of 4 mm were formed. According to various outer edge lengths, the results of self-inductance, error, and absolute error rate obtained by calculation and simulation are shown in Table 2. The self-inductance values for various outer edge length are shown in Fig. 10. Absolute error rates according to various outer edge length are shown in Fig. 11.

When the figures and table are examined, the self-inductance values increase as the outer edge length in PSC increases. For the modified Wheeler formula, the error occurred between 0.01 µH and 28.35 µH, and the absolute...
The absolute error rate was 0.1%. In the self-inductance calculation of the proposed sheet formula, the error occurred between 0.1 µH and 3.5 µH, and the absolute error rate was 0.1 % below.

Table 1. The results of self-inductance, error and absolute error rate obtained by calculation and simulation for various number of turns

<table>
<thead>
<tr>
<th>N</th>
<th>L_{Max} (µH)</th>
<th>L_{Squ} (µH)</th>
<th>H_{Squ} (µH)</th>
<th>ε_{Squ} (%)</th>
<th>L_{Whe} (µH)</th>
<th>H_{Whe} (µH)</th>
<th>ε_{Whe} (%)</th>
<th>L_{CS} (µH)</th>
<th>H_{CS} (µH)</th>
<th>ε_{CS} (%)</th>
</tr>
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<tbody>
<tr>
<td>3</td>
<td>14.6279</td>
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<td>0.0051</td>
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Table 2. The results of self-inductance, error and absolute error rate obtained by calculation and simulation for various outer edge length

<table>
<thead>
<tr>
<th>D_{out} (mm)</th>
<th>L_{Max} (µH)</th>
<th>L_{Squ} (µH)</th>
<th>H_{Squ} (µH)</th>
<th>ε_{Squ} (%)</th>
<th>L_{Whe} (µH)</th>
<th>H_{Whe} (µH)</th>
<th>ε_{Whe} (%)</th>
<th>L_{CS} (µH)</th>
<th>H_{CS} (µH)</th>
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Fig. 8. PSC self-inductances for various numbers of turns

Fig. 9. PSC absolute error rates for various numbers of turns

C. Distance Between Conductors

In order to examine the inductance calculations according to the various distance between conductors, PSCs were designed by keeping the other variables constant. PSCs were formed. According to the distance between conductors, the results of self-inductance, error, and absolute error rate obtained by calculation and simulation are shown in Table 3.
The self-inductance values for the distance between conductors are shown in Fig. 12. Absolute error rates according to various distance between conductors are shown in Fig. 13.

When the figures and table are examined, the self-inductance values decreased as the distance between conductors in PSC increases. For the modified Wheeler formula, the error occurred between 0.05 µH and 21.75 µH, and the absolute error rate was between 0.06% and 14.55%. For the Current sheet formula, the error occurred between 0.2 µH and 3.4 µH, and the absolute error rate was between 0.3% and 9.65%. For the proposed method, the error occurred between 0.02 µH and 0.1 µH, and the absolute error rate was between 0.01% and 0.2%. In the self-inductance calculation of the proposed method, it gave better results for various distance between conductors than other methods. The error was 0.1 µH below and the absolute error rate was 0.2% below.

**D. Distance Between Conductors**

In order to examine the inductance calculations according to the various conductor diameters, PSCs were designed by keeping the other variables constant. PSCs with a number of turns of 10, outer edge length of 500 mm, and distance between conductors of 4 mm were formed. According to various conductor diameters, the results of self-inductance, error, and absolute error rate obtained by calculation and simulation are shown in Table 4.
When the figures and table are examined, the self-inductance values decreased as the conductor diameter in PSC increases. For the modified Wheeler formula, the error occurred between 0.25 μH and 8.6 μH, and the absolute error rate was between 0.75% and 7.35%. For the Current sheet formula, the error occurred between 0.7 μH and 2.8 μH, and the absolute error rate was between 0.7% and 5.95%. For the proposed method, the error occurred between 0.1 μH and 0.4 μH, and the absolute error rate was between 0.1% and 0.4%. It is seen that the proposed method gives better results in the calculation of self-inductance when compared to other methods for various conductor diameters. The error was 0.4 μH below and the absolute error rate was 0.4% below.

Table 3. The results of self-inductance, error and absolute error rate obtained by calculation and simulation for various distance between conductors

<table>
<thead>
<tr>
<th>s (mm)</th>
<th>$L_{Max}$ (μH)</th>
<th>$L_{Sim}$ (μH)</th>
<th>$H_{Sim}$ (μH)</th>
<th>$\varepsilon_{Sim}$ (%)</th>
<th>$L_{Wh}$ (μH)</th>
<th>$H_{Wh}$ (μH)</th>
<th>$\varepsilon_{Wh}$ (%)</th>
<th>$L_{CS}$ (μH)</th>
<th>$H_{CS}$ (μH)</th>
<th>$\varepsilon_{CS}$ (%)</th>
</tr>
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<tr>
<td>0,1</td>
<td>149,5799</td>
<td>149,6048</td>
<td>-0.025</td>
<td>0.0166</td>
<td>127,8658</td>
<td>21,7141</td>
<td>14,5167</td>
<td>152,96</td>
<td>-3.38</td>
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<td>2,5</td>
<td>114,4529</td>
<td>114,3551</td>
<td>0.0978</td>
<td>0.0854</td>
<td>108,9181</td>
<td>5,5348</td>
<td>4,8359</td>
<td>116,597</td>
<td>-2,144</td>
<td>1,8733</td>
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<tr>
<td>4</td>
<td>100,6015</td>
<td>100,5453</td>
<td>0.0562</td>
<td>0.0559</td>
<td>98,5346</td>
<td>2,6699</td>
<td>2,0545</td>
<td>102,067</td>
<td>-1,4656</td>
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<tr>
<td>6,25</td>
<td>84,7956</td>
<td>84,7496</td>
<td>0.046</td>
<td>0.0542</td>
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<td>0.0559</td>
<td>0.0659</td>
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<tr>
<td>9</td>
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<td>69,9962</td>
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<td>70,3391</td>
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<tr>
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<td>59,2651</td>
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<td>0.0957</td>
<td>59,2064</td>
<td>0.1155</td>
<td>0.1947</td>
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<tr>
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<td>50,3018</td>
<td>0.0578</td>
<td>0.1148</td>
<td>49,6361</td>
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<td>1.4367</td>
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<tr>
<td>17</td>
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<td>0.1807</td>
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<td>3.6237</td>
<td>39,7215</td>
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<tr>
<td>19</td>
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<td>0.0706</td>
<td>0.1946</td>
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<td>5.4616</td>
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<td>0.114</td>
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<td>2.4244</td>
<td>7.6351</td>
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<td>2.9143</td>
<td>10.4674</td>
<td>25,553</td>
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<td>12.8629</td>
<td>23,1697</td>
<td>2.4691</td>
<td>9.6303</td>
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</table>

In Table V, maximum and minimum error rates are given for different methods according to the number of turns, outer diameter, spacing between cables and cable thickness. As can be seen from Table 5, this method has a lower error rate than other methods. In addition, while other methods are affected by the changes in various coil design parameters, this method is almost unaffected by these parameter changes.

5 Conclusions

One of the most crucial parts of WPT applications is coil design. The paper introduces a novel self-inductance calculation model for planar spiral square coils. Various self-inductance calculation methods have been presented in the literature. However, the error rates of many methods may increase depending on the coil geometry. In addition to these methods, the proposed method was tested for different design parameters such as different outer diameters, spacing between turns, and the number of turns. The results of the proposed method and ANSYS Maxwell 3D simulation results were compared. The proposed approach calculated the self-inductance of PSCs with an error rate of less than 0.4% and an error of less than 0.45 μH. Moreover, the proposed
method was compared with other methods in the literature. The error rate of this method is much lower than other methods.

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References