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Optimization of a Circular Planar Spiral Wireless Power Transfer Coil Using a Genetic Algorithm

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Abstract: Circular planar spiral coils are the most important parts of wireless power transfer systems. This paper presents the optimization of wireless power transfer coils used for wireless power transfer, which is a problem when designing wireless power transfer systems. A single transmitter coil transfers power to a single receiving side. The performance of the wireless power transfer system depends greatly on the size and shape of the wireless power transfer system. Therefore, the optimization of the coils is of the utmost importance. The main optimization parameter was the coupling coefficient between the transmitter and the receiver coil in the horizontally aligned and misaligned position. A genetic evolutionary algorithm was used to optimize the coil, according to the developed cost function. The algorithm was implemented using the MATLAB programming language. The constraints regarding the design of the coils are also presented for the problem to be analyzed correctly. The results obtained using the genetic algorithm were first verified using FEM simulations. The optimized coils were later fabricated and measured to confirm the theory.

Keywords: wireless power transfer; coil optimization; genetic algorithm; coupling coefficient measurement



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1. Introduction

In the last few years, wireless power transfer (WPT) has become very popular [1,2]. Among the multiple transfer methods, the most popular are inductive and inductive resonant wireless power transfer [3–5]. Inductive wireless power transfer, or IPT, transfers energy using high-frequency magnetic fields. The strength of the magnetic field must not exceed the values proposed by the standards for non-ionizing electromagnetic fields [6]. This means that the wireless charging is completely safe to use.

The basic coil structure consists of a single transmitter and a single receiver coil. In this case, the transmitter and the receiver coil have a circular design and the same properties. The main properties of the coils are the wire diameter, the coil's maximum radius, and the distance between the turns, or pitch. The alternating current in the transmitter coil generates a variable magnetic field. The radiated field is usually nondirectional and can therefore be limited only by the coil size and shielding materials. An alternating voltage is induced in the receiver coil if the coil is in the proximity of the generated magnetic field. In consumer electronics, the power that IPT can transfer is limited when using different standards, and the same is true for the operational frequency and the communication protocols between the transmitter and the receiver.

The most popular devices where wireless charging has been implemented are smartphones and other wearable tech. The standard covering low-energy power transfer is the Qi standard, which covers wireless power transfer up to 15 W [7,8]. Qi chargers with higher power can be used to charge laptops and other more power-demanding portable devices.

Due to the popularity of the Qi wireless charging standard, different commercially available coil solutions are also available. The coils are smaller in size, with low self-inductance and a low power transfer range [9]. Larger transmitter and receiver coils

are used in order to increase the range of wireless power transfer. Other than that, the operational frequency can also be increased in order to increase the quality factor of the power transfer and increase the efficiency at small coupling coefficients [10].

A method for optimization of the transmitter and the receiver coil is presented in this paper. The optimization is based on the self-inductances of the transmitter and the mutual inductance between them. Additionally, the inductance of the coils is also taken into account. This research was limited to planar circular spiral coils, which are one of the most popular wireless charging coil types. Other types of planar coils include square or rectangular planar spiral coils, or, in special cases, bipolar double D coils with directional magnetic fields [11]. However, in generic applications, the coils with directional magnetic fields are not suitable due to a more difficult design and fabrication process.

The main advantage of the proposed algorithm is to help design the optimal wireless power transfer coil if the maximum allowed radius of the coils is known. The transmitter and the receiver can have the same or a different radius, depending on the application the coil is used in. The solution received from the algorithm can then be verified using simulation software and practical implementation and measurements. The proposed method is particularly useful for designing planar spiral coils, which are the easiest to manufacture and implement. The results from the algorithm can be used for coils with the same and different radii. The algorithm is designed to take the misalignment among the coils into account. Most coil optimizations tackle the problems of complex coil shapes or the development of different coil shapes [12,13]. However, there is little research on how to select the most appropriate spiral coils. Most studies, including this one, have used genetic algorithms for the selection and development of the coil parameters. However, the main differences are in the fitness function for which the parameters are developed.

This paper is structured as follows. First, after the introduction, the basic structure of the typical wireless power transfer system is presented using a single transmitter and receiver coil. The third chapter describes the calculation of the self and mutual inductance of the planar circular spiral coils. The structure of the genetic algorithm used to optimize the transmitter and the receiver coil is presented in the Section 4. This includes the basic algorithm structure. The optimization results are presented in the Section 5. Lastly, the Sections 6 and 7 present the discussion and the conclusion of this paper.

2. Basic Structure of Wireless Power Transfer Systems

The inductive power transfer (IPT) system consists of two parts. The first part is the transmitter, and the second part is the receiver. The basic structure is presented in Figure 1. The main parts of the transmitter are the high-frequency inverter and the transmitter coil, which is compensated using a compensation circuit. The secondary part consists of a compensated receiver coil and a full-wave rectifier. The rectifier can be further connected to an additional DC/DC converter, which is then used to transfer power to the load. In the case of the system described in this paper, the load is connected directly to the rectifier. In most applications, the resistive load is usually replaced by a battery or battery charging system.

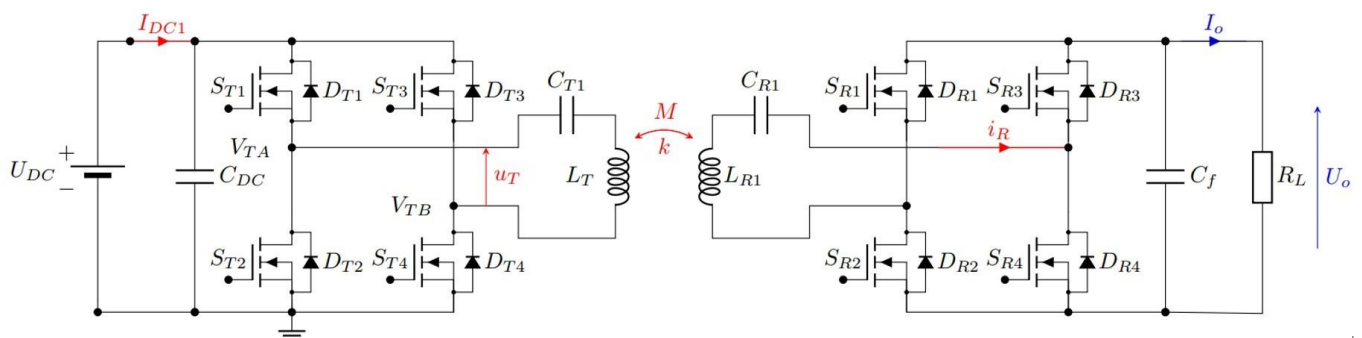


Figure 1. Basic structure of an inductive wireless transfer system using a single transmitter and receiver coil.

In the case of the IPT system presented in Figure 1, the basic series–series is used, or SS compensation. The main advantage of an SS compensation system is a fixed operating frequency, independent of the mutual inductance between the transmitter and the receiver coil [14]. Additional benefits include the design simplicity and symmetry that can be used in bidirectional wireless power transfer. The resonant frequency of the system is calculated using the following equation:

$$\omega_r = \frac{1}{\sqrt{L_T C_T}} = \frac{1}{\sqrt{L_R C_R}} \quad (1)$$

where L_T and C_T are the transmitter coil self-inductance and primary compensating capacitance, and L_R and C_R are the receiver coil self-inductance and the secondary compensating capacitance.

The resonant frequency of the system is usually determined by the application where the IPT system will be used. Usually, the frequencies range from tens of kHz to MHz. Currently, in commercially available applications, in the case of Qi wireless, the charging frequency is around 150 kHz. In the automotive industry, the SAE J2954 standard proposes lower operating frequencies of around 85 kHz [15,16]. Many commercially available transmitter and receiver coils can be purchased due to the popularity of low-power device charging using the Qi standard. Due to their small size, they are used for distances of up to a centimeter. However, if the distance between the transmitter and the receiver is small, the coils can become over-coupled, which results in frequency-splitting phenomena [17]. On the other hand, coils for IPT with higher power need to be fabricated for specific applications. This means that the outer and inner dimensions, number of turns, thickness of the wire, and pitch between the turns are all selected by researchers and manufacturers. The size of the coils is usually limited by the maximum allowed dimensions and thickness of the wire, determined by the current flowing through the primary and secondary coils. Therefore, a genetic algorithm can be used to optimize the number of turns and distances between turns to ensure the optimal coupling coefficient between the transmitter and the receiver coil.

3. Calculating the Mutual Inductance between the Transmitter and Receiver Coil

The main qualifier of the performance and the main contribution to the cost function of the genetic algorithm is the mutual inductance between the transmitter and the receiver coil. The mutual inductance greatly impacts the efficiency and the misalignment tolerance between the primary and the secondary coil. The second qualifier is the self-inductance of the transmitter and the receiver coil. Coils with larger self-inductances can generate larger magnetic fields, which transfer more power. This results in faster charging capabilities.

During the optimization, the calculations were performed using the program MATLAB. This program enables the integration and calculation of the different elliptical integrals, which can speed up the development process.

A basic spiral coil consists of multiple concentric turns [18]. To simplify the model, the coil can be represented using discrete turns with different radii. The basic transmitter/receiver coil structure is presented in Figure 2. The radius of the wire is marked with the parameter r . The pitch between the turns is marked with w . Lastly, the inner and outer diameters are marked with R_{in} and R_{out} , respectively. The resulting coil consists of the sum of concentric circular loops with different radii.

The simplified self-inductance, therefore, consists of the loop self-inductances and mutual inductances between the turns. The self-inductance of a single circular loop can be calculated using the following equation [16]:

$$L_i = \mu_0 R_i \left(\ln \left(\frac{8R_i}{r} \right) - 2 \right) \quad (2)$$

where L_i is the i -th loop self-inductance, R_i is the loop radius, and r is the radius of the wire.

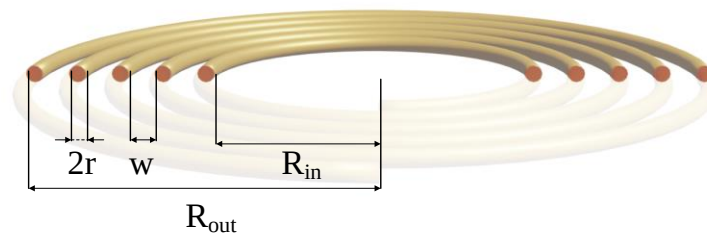


Figure 2. Dimensions of a circular planar spiral coil.

The mutual inductance between the concentric turns can be calculated using the following equation:

$$M_{ij} = \mu_0 \sqrt{R_i R_j} \left(\left(\frac{2}{k_{ij}} - k_{ij} \right) K_{ij} - \frac{2}{k_{ij}} E_{ij} \right) \quad (3)$$

where M_{ij} is the self-inductance between the i -th and j -th turns, R_i and R_j are the radii of the i -th and j -th turns, and K_{ij} and E_{ij} are the first- and the second-order elliptical integrals, which depend on the parameter k_{ij} , the elliptic module of eccentricity. The parameter can be calculated using the following equation:

$$k_{ij} = 2 \sqrt{\frac{R_i R_j}{|R_i + R_j|^2}} \quad (4)$$

Finally, the self-inductance of the coil with specific dimensions and numbers of turns can be calculated using the following equation:

$$L = \sum_{i=1}^N L_i + \sum_{i=1}^{N, i \neq j} \sum_{j=1}^{N, i \neq j} M_{ij} \quad (5)$$

The first part of the equation consists of the self-inductances of the loops, and the second part consists of the mutual inductance between the i -th and j -th turn. It is important that the mutual inductance is calculated only between the turns with different radiuses, meaning that i is not equal to j because of the limitations of Equation (3).

Figure 3 presents the single transmitter and single receiver loop with a distance d between them. The diameter of the transmitter loop is marked with R_1 , and the diameter of the receiver loop is marked with R_2 . When calculating the mutual inductance, the radius of the wire is not important.

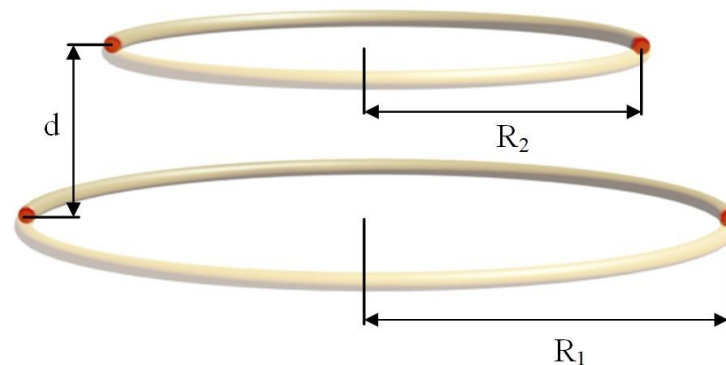


Figure 3. Sketch of single transmitter and single receiver coil loop.

The mutual inductance between two concentric turns can also be calculated using the double integral equation as an alternative to the equation using elliptical integrals. The

equation does not use the first-order or second-order elliptical integrals E_{ij} and K_{ij} and is therefore more computationally taxing.

$$M_{ij} = \frac{\mu_0}{4\pi} \int_0^{2\pi} \int_0^{2\pi} \frac{\sin(\theta) \sin(\varphi) + \cos(\theta) \cos(\varphi)}{\sqrt{(R_1 \cos(\theta) - R_2 \cos(\varphi))^2 + (R_1 \sin(\theta) - R_2 \sin(\varphi))^2 + d^2}} d\theta d\varphi \quad (6)$$

The mutual inductance between the transmitter and the receiver coil can also be impacted by horizontal misalignment. By misaligning the coils from their optimal position, the mutual inductance and therefore the coupling coefficient between the transmitter and the receiver coil decreases [19]. This results in a lower coupling coefficient and lower system efficiency. Usually, different types of coils or different compensation strategies are used in order to increase the transfer efficiency from using different coil types to using different, more complex compensation topologies.

$$M_{ij}(d) = \frac{\mu_0}{4\pi} \int_0^{2\pi} \int_0^{2\pi} \frac{\sin(\theta) \sin(\varphi) + \cos(\theta) \cos(\varphi)}{\sqrt{(R_1 \cos(\theta) - R_2 \cos(\varphi))^2 + (R_1 \sin(\theta) - R_2 \sin(\varphi) - y)^2 + d^2}} d\theta d\varphi \quad (7)$$

Based on Equation (7), the mutual inductance between the transmitter and the receiver coil can be calculated using the following equation:

$$M(y, d) = \sum_i^{N_i} \sum_j^{N_j} M_{ij}(y, d) \quad (8)$$

Usually, when describing the magnetic connection between the transmitter and receiver coil, a unitless coupling coefficient is used instead of mutual inductance. It can be calculated based on the mutual inductance and self-inductances of both coils:

$$k = \frac{M}{\sqrt{L_T L_R}} \quad (9)$$

where k is the coupling coefficient with values between 0 and 1, M is the mutual inductance between the coils, and L_T and L_R are the self-inductance of the transmitter and receiver coil, respectively.

Either way, if the fitness function uses a coupling coefficient or mutual inductance, higher values result in better magnetic coupling and therefore a higher and better efficiency.

4. Genetic Algorithm for Circular Spiral Coil Optimization

4.1. Basic Algorithm Description and Flowchart

An evolutionary algorithm called the genetic algorithm was used to optimize the mutual inductance between the transmitter and the receiver coil [20,21]. The algorithm was inspired by the process of natural selection. The operation of the algorithm can be summarized in a few key steps:

- First, the problem that we wanted to optimize was described using the parameters. In the case of the optimization of the circular coils, the most important parameters are the number of coil turns and the pitch between turns. The parameters are coded into genes, which are represented using an array. If we group multiple genes together, a population is born. The problem is usually also constrained by the physical properties of the optimization problem. In the case of wireless transfer coils, the bounds are the outer dimension of the coil, the connection between the turns' pitch and the number of turns, and the diameter of the wire. The constraints must be taken into account when generating the initial generation and during the gene crossover and mutation.

- The initial population must be generated at the start of the optimization. Usually, it is generated by selecting parameters with random numbers within the constraints. The initial population is used as a seed for the next generations.
- Each gene of the initial population is evaluated numerically using the fitness function. The fitness function is based on the optimization problem. It can consist of single or multiple criteria, in which case, each of the criteria must be weighted properly using an initially chosen constant. Based on the fitness function, the best-performing genes are chosen for crossover into the next generation. The best-performing genes can also be called parent genes.
- In the next step, the parent genes are used to create offspring genes, which inherit properties of both parent genes. During reproduction, additional gene mutations should also be introduced in order to avoid the problem of falling into the fitness function local maxima, which returns suboptimal results. The new genes are used in the next iteration of the genetic algorithm.
- New, recombined generations are again evaluated using the proposed fitness function, after which the best-performing genes are selected to generate a new population.
- The genetic algorithm continues to evolve until certain conditions are met. The condition can be based on the fitness function or on the number of iterations. In the case of coil optimization, the end of the algorithm is determined by the number of iterations.

The basic program structure is also presented in Figure 4. The most computationally heavy operation is calculating the fitness function. In order to select the most optimal mutual inductance, each fitness function includes the calculation of the mutual inductance, which includes the calculation of the double integral. This can take a longer time, especially if the transmitter and receiver coils have large numbers of turns.

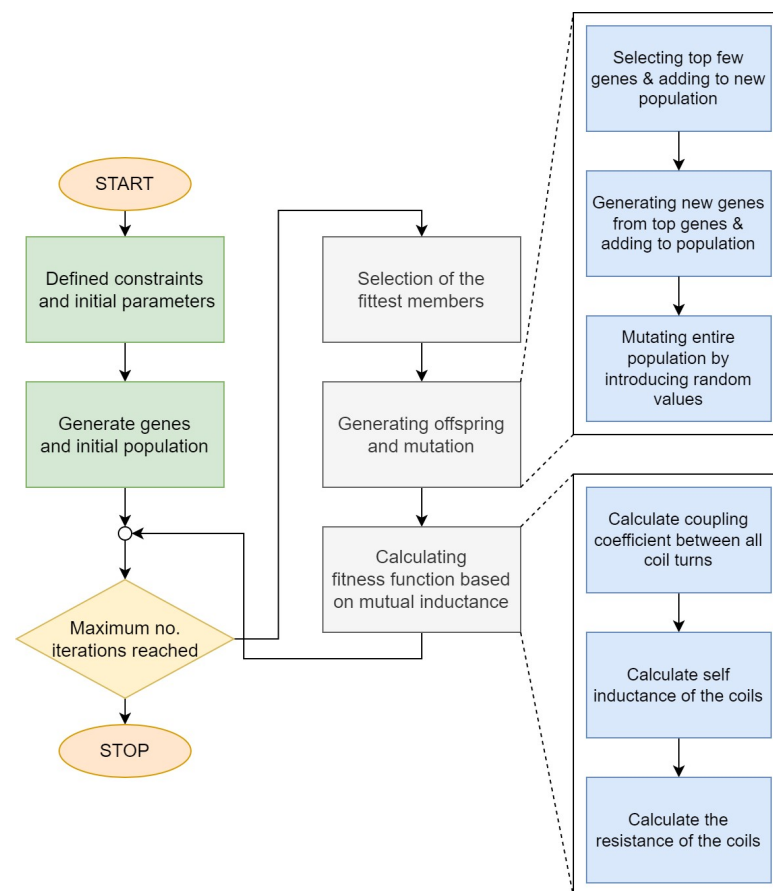


Figure 4. Block diagram of the proposed genetic algorithm.

4.2. Gene Structure, Genetic Crossover, and Mutation

The structure of the gene depends on the size of the transmitter and receiver coils. The connection between the physical properties of the coil design and the gene is called gene coding. In cases where the transmitter and the receiver coil have the same dimensions, the parameters coded in the gene are the number of turns and the pitch between the turns. In cases where the dimensions between the transmitter and the receiver are different, the gene requires four parameters: the number of turns for the transmitter and the receiver coil, and the pitch between the turns in the transmitter and in the receiver coil.

The main criteria for fitness were the coupling coefficients between the transmitter and the receiver coils when the coils were misaligned in a selected region. The second parameter was the self-inductance of the transmitter and receiver coil, and the last parameter was the resistance of the receiver and transmitter coil. The fitness function has the following form:

$$f = \alpha \sum k + \beta L - \gamma R \quad (10)$$

where the constants α , β , and γ represent the weights of specific parameters. Parameter k is the coupling coefficient between the transmitter and receiver coil, parameter L is the self-inductance of the transmitter/receiver coil, and R is the DC resistance of the transmitter/receiver coil. All three parameters are dependent on the physical properties of the transmitter and the receiver coils.

In order to obtain the results, the generation after the initial generation had a different structure. It can be divided into three different sections:

- The first section includes the top genes carried over from the previous iteration. Therefore, the best ones remain if the newly mutated genes are worse than the original genes.
- The second section includes the offspring generated from the top genes. The offspring are generated by switching the parameters between two different genes and later by calculating the average values between the two genes.
- The third section is a mutation of the offspring. Each gene generated from the top genes in the previous generation is mutated by adding a random value to the parameters. This results in different parameter values that can be used to evaluate the performance of the optimized coil further.
- After generating new genes with crossover and mutation, the fitness function is calculated again, and the top genes are selected again. In the case of coil optimization, the process is stopped after a certain number of cycles or generations. The evolved optimal coil can be tested using simulation software or by fabrication.

5. Coil Optimization Results

5.1. Computer-Simulated Results

Two different coil optimizations were tested to test the proposed genetic algorithm. The first optimization was for the coils with the same dimensions, and the second optimization was for the coils with different dimensions. The results are presented in Figures 5 and 6. In all four graphs, the blue line represents the results obtained from the optimization. The red and yellow lines represent the results of the suboptimal coils, which resulted from changing the parameters of the optimized coils, for instance, by adding another turn or increasing the turn pitch.

The constraints for the coil presented in Figure 5 are a maximum outer radius of 5 cm. The results obtained from the optimization algorithm are 19 turns with a 0 mm pitch. The red lines in Figure 5a,b represent the coil with 19 turns and a 1mm pitch. The yellow line represents the results obtained by increasing the number of turns by 1 and by changing the pitch to 5 mm.

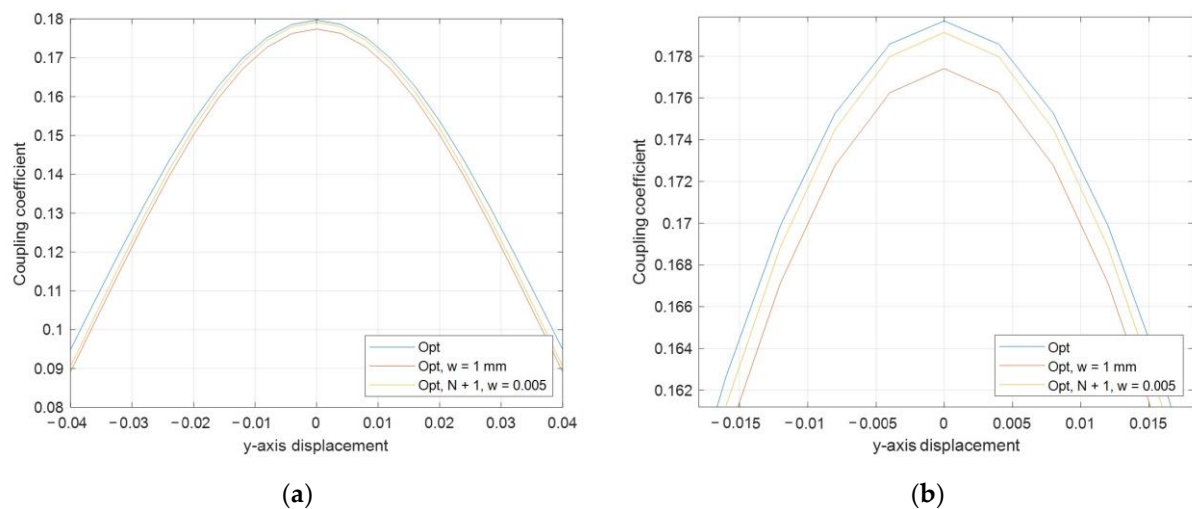


Figure 5. The results of the optimization for circular planar spiral coils with the same diameters: (a) y -axis displacement from -0.04 m to 0.04 m; (b) zoomed-in view from -0.015 m to 0.015 m.

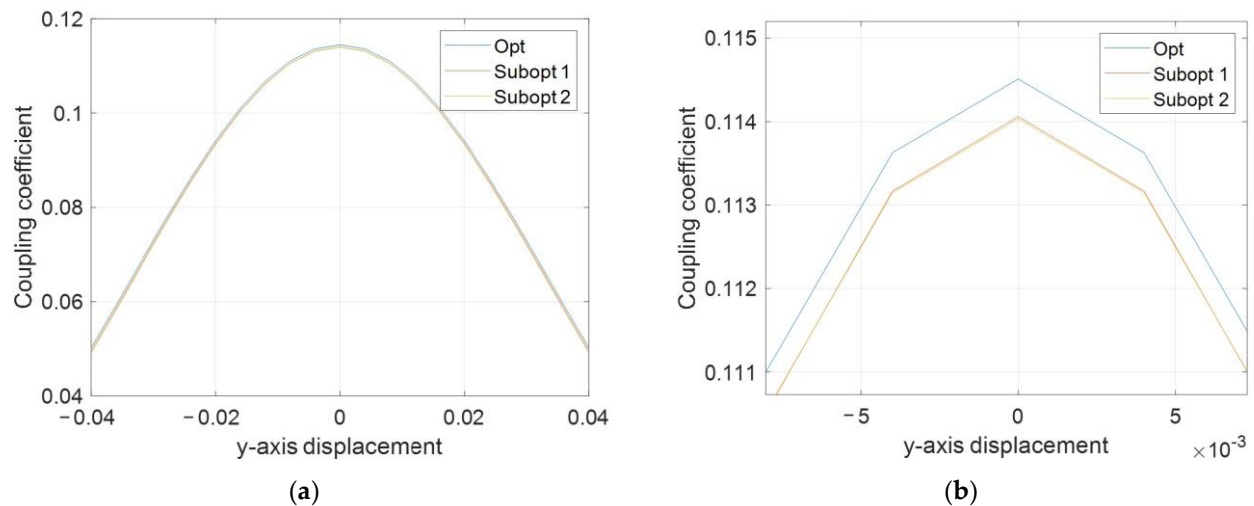


Figure 6. The results of the optimization for circular planar spiral coils with different diameters: (a) y -axis displacement from -0.04 m to 0.04 m; (b) zoomed-in view from -0.012 m to 0.012 m.

The constraints for the case presented in Figure 6 were a first coil with a maximum outer radius of 5 cm and a second coil with a maximum radius of 3 cm. The results obtained from the optimization algorithm were as follows: the first coil had 24 turns and 0 mm pitch, and the second coil had 5 turns and 1 mm pitch. The red line in Figure 5a,b represents the large coil with 25 turns and a 0 mm pitch, and the second coil had 5 turns and a 5 mm pitch. The yellow line represents the large coil with 24 turns and a 0 mm pitch, and the second coil had 6 turns and a 0 mm pitch.

To confirm that the algorithm and the coupling coefficient, calculated using the proposed equation, provided the correct results, both optimization problems were tested using the simulation software Ansys Maxwell. The results are presented in Figure 7. The calculated results are presented with the blue line and the simulated results are presented with the orange line. Figure 7a presents the results in the case when both coils have the same diameter, and Figure 7b presents the results in the case when the receiver coil has a smaller diameter than the transmitter coil. From the results, it can be seen that the simulation results are nearly identical to the calculated results. There is some difference; however, it is not significant, and the simulation can be used to confirm that the equations correctly describe the coils.

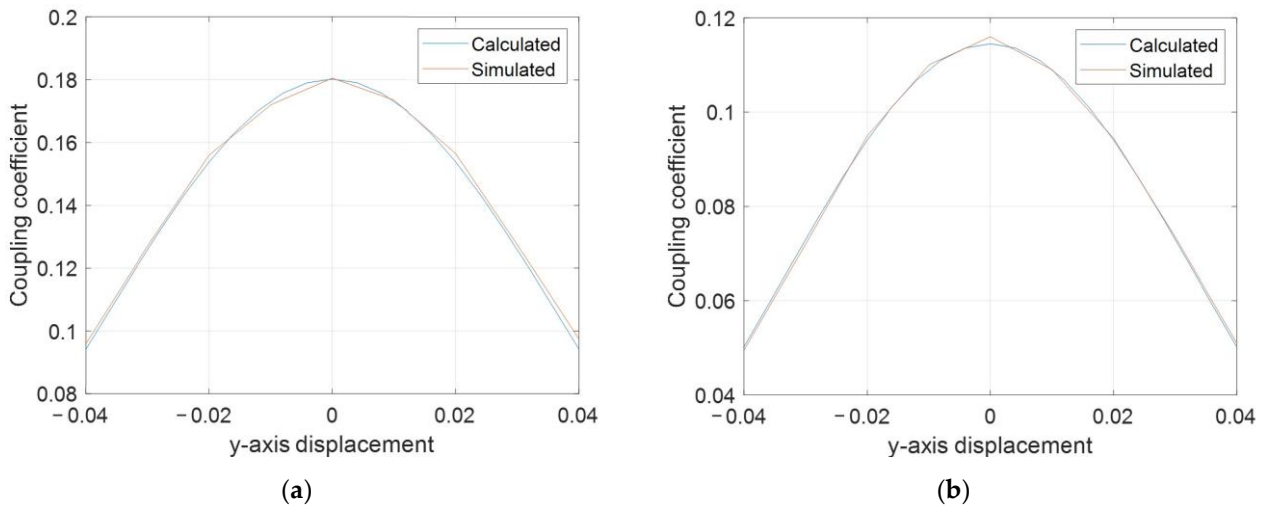


Figure 7. Comparison between the algorithm and simulation results: (a) first optimization case; (b) second optimization case.

5.2. Experimental Measurement Setup and Verification

In order to confirm the theory behind the coil optimization using the proposed method, the coil was fabricated and tested using an experimental set bench.

To measure the mutual inductance between the transmitter and the receiver coil, an offline method was used using an LRC meter. When two inductances are connected in a series, mutual inductance is also added or subtracted in addition to the sum of the coil self-inductances. In the case of constructive mutual inductance, the RLC meter measures the inductance L_{X1} , which can be calculated using Equation (11) [22,23]. In the case of destructive mutual inductance, the RLC meter measures the inductance L_{X2} , which can be calculated using Equation (12).

$$L_{X1} = L_T + L_R + 2M \quad (11)$$

$$L_{X2} = L_T + L_R - 2M \quad (12)$$

By measuring the inductance value in the presence of constructive and destructive mutual inductances, the mutual inductance can be measured without the requirement of knowing the self-inductances of the transmitter and the receiver coils.

$$M = \frac{L_{X1} - L_{X2}}{4} \quad (13)$$

The mutual inductance and the coupling coefficient between the transmitter and the receiver coil were measured using the RLC meter. In order to position the transmitter and the receiver coil correctly, the coils were mounted onto the computer-controlled positioning system presented in Figure 8. The transmitter coil was mounted on the bottom platform, which could be moved in the horizontal x and y directions. The receiver coil was mounted on the top platform, which could be moved in the vertical z direction. In the current configuration, the system does not allow for the measurement of rotational tolerance.

The coils were connected to a switching matrix, which switches between four different configurations. The first two are for measuring the self-inductance of the transmitter and the receiver coil, the third is for measuring the inductance of the coils connected in a series with constructive mutual inductance, and the fourth is for measuring the series inductance in the case of destructive mutual inductance.

The output of the matrix was connected to the RLC meter, which was then used to measure each of the inductances. Currently, all measurements must be performed by hand, which can take a long time.

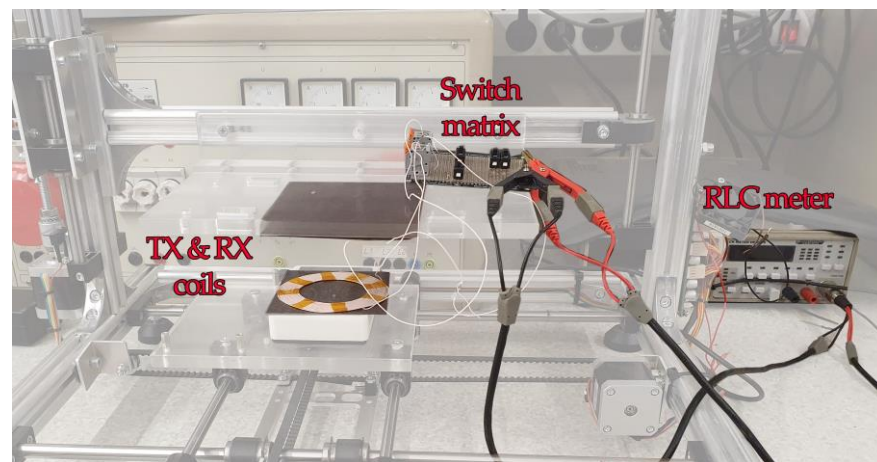


Figure 8. Experimental test bench for controlled measurement of the mutual inductance between two coils.

Figure 9 presents the results of a comparison between the fabricated coil and calculated results based on the equations presented in Section 3. The blue line represents the calculated coupling coefficient, and the red line represents the measured coupling coefficient. When the coils are perfectly aligned, the calculated coupling coefficient is larger than the measured value. However, at higher misalignments, the coupling coefficients are virtually the same. The main difference in the results is due to the simplification of the coil equations and defects in the coil manufacturing process. In the case of this paper, the coils were made by hand. However, despite the difference, the proposed algorithm can still help in the design process of wireless power transfer. Using the coil's maximum dimensions, the optimal coil with the optimal number of turns and pitch degree can be evolved.

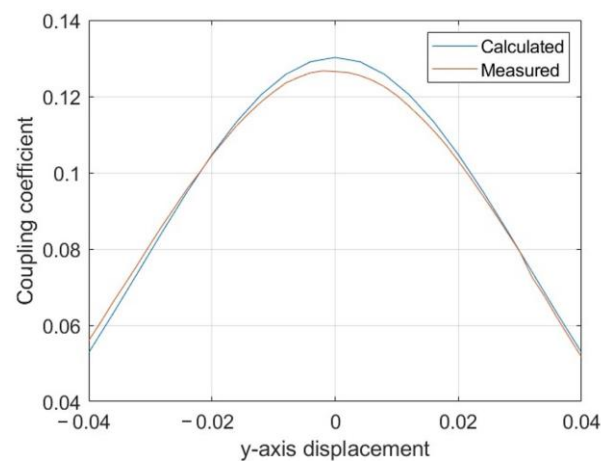


Figure 9. Comparison between mutual inductance calculation and RLC-based measurement.

6. Discussion

In the presented configuration, the proposed genetic algorithm can only be used to optimize the classic circular planar spiral coils with a constant pitch between the turns. However, wireless power transfer systems can use different coil shapes, from square and rectangular shapes to bipolar coil structures. Therefore, in order to optimize for different coil designs, a new gene structure and a new cost function should be used. When using more complex coil shapes, the cost function becomes more complex and therefore more computationally time-consuming. However, the transmitter and the receiver coil structures can be optimized, as long as the algorithm does not converge to the local minimum. The

crossover function and the mutation of the gene offspring should be designed so that the algorithm searches for the global minimum.

The results of the algorithm were tested first using the simulation software and later using the experimental mutual inductance and coupling coefficient measurements. The simulation results were nearly identical to the results obtained using the equations and the cost function calculation. However, there was a greater difference between the calculated coils and the experimental and practical measurements. The main cause of this is that the equations only present the simplified solution used to calculate the inductance and mutual inductance between the coils. In addition, the fabricated coils were not fabricated perfectly. They were fabricated by hand, which can result in a noncircular shape and different pitches between turns. The solution to this is automated coil fabrication or coil implementation using printed circuit boards.

7. Conclusions

One of the greatest challenges in IPT design is designing custom transmitter and receiver coils for wireless power transfer. Therefore, this paper presents the genetic algorithm to aid in the development of circular spiral coils. The cost function of the genetic algorithm is based on the self and mutual inductances for calculating the fitness function used to train the genetic algorithm. The main goal of the genetic algorithm was to determine the physical properties of the transmitter and the receiver coil in order to ensure an optimal coupling coefficient between the transmitter and the receiver coil. The algorithm can be used to calculate the optimal transmitter and receiver coil with the same or different diameters. The main constraints are the maximum outer dimensions and the thickness or diameter of the wire.

In order to confirm the theory behind the operation, the coils were also fabricated and tested using a test workbench with a controlled positioning mechanism. Only the coupling coefficient between the transmitter and the receiver coil was tested. In the future, the entire system integration could be optimized using the genetic algorithm. This would result in better performance of the IPT system and increased efficiency.

The main limitation of the presented method is that it can only be used to optimize coils without ferrite shielding, which is known to direct the magnetic field and increase the system's efficiency. However, currently, none of the equations describing the calculation of self and mutual inductance are able to account for the effects of the included ferrite plate. Additionally, this method is limited to coils with the same spacing between turns. Such coils are easier to implement. On the other hand, the distribution of the magnetic field and the coupling coefficient between the coils could be suboptimal.

Future research could include the genetic optimization of different, more complex coil shapes, such as double D or DD coil shapes. These shapes consist of two planar rectangular coils connected in the series, which complicates the formula for the calculation of self and mutual inductance. The basic algorithm would stay the same; only the cost function would be different.

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