Genetic Algorithm Based Optimization of Circular Planar Coil Geometry With Homogeneous Magnetic Field Distribution

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***Abstract*—A prominent problem in planar resonant wireless power transfer (WPT) systems is instability of efficiency and load power due to position misalignment of the receiver (RX) coil relative to postion of the transmitter (TX) coil. In order to keep stable efficiency and load power even in such misaligned condition it is necessary to design transmitter coil which generates homogeneous magnetic field in charging plane. In this paper, a geometry of planar transmitter coil which consist of multiple concentric circles is optimized by utilizing genetic algorithm. Optimization goal is achieving as large as possible homogeneous region, i.e. portion of charging plane which is characterized by homogeneous magnetic field. Magnetic field evaluations are done by FEMM software. Proposed coil achieves continuous homogeneous region at 44.4% surface of charging plane. Optimized coil and its homogenous region is compared to the state-of-the-art.**

***Keywords*—coil, genetic algorithm, optimization, resonant wireless power transfer**

I. INTRODUCTION

In recent decades, interest in wireless power transfer (WPT) is growing rapidly. This is due to an increase in usage of rechargeable battery powered devices: consumer electronics, [1], electric vehicles (EVs), [2], and implanted medical devices, [3]. In comparison with conventional wired charging, WPT reduces electrical shock hazard as a result of not involving wired connection between source of energy and battery. Besides, using WPT eliminates development of mechanical damage of power connectors in conventional and manual pluging on a daily basis. Instead of doing surgical operation in order to replace batteries of implanted medical devices, more convenient WPT is applied to reduce health risks.

Depending upon time variant physical fields which are the mediators for energy transfer, there is capacitive (electric fields) and inductive (magnetic fields) WPT. Working principle of a two coil inductive WPT system is that changing magnetic field of transmitter (TX) coil induces voltage at receiver (RX) coil. Efficient power transfer is limited to about 1 cm range, [4]. Groundbreaking paper, [5], introduced resonant inductive wireless power transfer (RIWPT) system. Simplified model of such system consists of two LC oscillators which operate at the same resonant frequency. General properties of efficient RIWPT system are: high quality factors of TX and RX coils and low value of magnetic coupling coefficient k. In RIWPT system, k is typically less than 0.15, [4], [6].

Generally, coupling coefficient value is dependent on the distance, d, between TX coil and RX coil. Small coupling coefficient value in RIWPT system implies larger transfer distance and eventually, a transfer of energy towards multiple RX coils that are significantly smaller compared to TX coil. Although efficient power transfer is feasible even for small coupling coefficient value (larger transfer distance), conventional RIWPT system (TX coil and RX coil are situated in parallel planes) requires precise or coaxial alignment of RX coil position relative to TX coil position. Situation in which centers of coupled TX coil and RX coil are horizontally displaced is referred to as lateral misalignment, [7]. However, accurate positioning of coils is not so easy task in real life scenarios. For example, precise alignment of coil integrated in EV, coaxial alignment of RX coil of implanted medical device under the tissue and so on.

Since lateral misalignment causes nonstable efficiency and load power in conventional RIWPT, authors propose two approaches to keep them more stable. First, tracking resonant frequency shift and tuning system to new resonant frequency which occurs in phenomenon called frequency splitting, [4], [8], [9]. Adapting to new resonant frequency is equivalent to procedure of impedance matching. Second, generating homogeneous magnetic field distribution is proposed to prevent frequency splitting and impedance mismatching in lateral misalignment condition. In other words, various TX coil designs are proposed to generate homogeneous magnetic field distribution at the charging plane of RIWPT.

Proposed 2D TX coil designs would be systemized as follows: hybrid, spiral and specific structure. Hybrid coils are composed of outer ring coil and inner spiral coil connected in series, [10], [11]. Spiral coils are charcterized by specific and nonuniform spacing between adjacent turns, [12]–[17]. Coils with specific design are: coil formed of concentric circles, [18], Taichi coil, [19], and coil with intertwined turns, [20]. Proposed 3D coils are the ones that occupy certain volume which keeps them distinct from proposed 2D coils. Hybrid, [21], funnel type, [22] and rectangular coils, [23]–[25], are proposed as 3D coil solutions.

Following section analyzes nonhomogeneity of magnetic fields in charging plane above conventional TX coils. Third section deals with the optimization of a coil made up of concentric circles. Genetic algorithm was used as an optimization tool. At the end, the conclusion is derived.

II. MAGNETIC FIELD DISTRIBUTION ANALYSIS

RX coils in planar RIWPT are placed within charging plane which is lightly shaded in Fig. 1. Surface of charging plane corresponds to surface enclosed by TX coil outline. Hence, charging plane radius, *r*, is equal to TX coil radius, r_{out}. Charging plane (RX coils) and TX coil are vertically separated by distance *d*. Magnetic field intensity distribution at charging plane is a matter of interest.

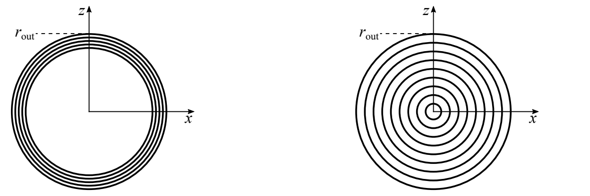
According to well known Faraday-Lenz law, the voltage induced in a coil is proportional to the time varying magnetic flux, ϕ. Equation which describes magnetic flux which passes through some area A is following:

$$\phi = \vec{B} \cdot \vec{A} = \mu \cdot |\vec{H}| \cdot |\vec{A}| \cdot \cos(\alpha) = \mu \cdot |\vec{H}_y| \cdot |\vec{A}|, \quad (1)$$

where, $\vec{B}$ is the magnetic flux density, $\vec{A}$ is the vector normal to an area A. Magnitude of vector $\vec{A}$ is equal to surface of observed area A through which magnetic flux is passing. The magnetic field intensity, $\vec{H}$, and $\vec{B}$ are mutually proportional and the constant of proportionality is the permeability, μ. Finally, α is the angle between $\vec{A}$ and $\vec{H}$. From (1) and according to the Fig. 1, it is obvious that the only component of magnetic field intensity that is perpendicular to the charging plane, $\vec{H}_y$, contributes to magnetic flux. Thus, solely vertical component of the magnetic field intensity is considered in the rest of this paper.

Conventional planar ring coil and concentric circles coil are shown in the Fig. 2. Both coil designs are created in FEMM (Finite Element Method Magnetics) software and simulations are carried out to determine magnetic field intensity in charging plane that is 10 mm above (d = 10 mm). Turns of coils are made of copper and surrounding environment is air ($\mu = \mu_0 \cdot \mu_{air} \approx \mu_0$). Parameters of both simulated coils are shown in the Table I. In FEMM, both coils are defined as axisymmetric problem since doing a 360° rotation of turns cross sections around axis forms complete 3D coil models. For the reason that problem is axisymmetric, examining magnetic field intensity in charging plane is simplified to charging line that is eventually a radius of circular charging plane, *r*, depicted as dashed line in the Fig. 1.

Normalized magnetic field intensity in charging line above ring coil and concentric circles coil is shown in Fig. 3 and Fig. 4, respectively. Magnetic field intensity distribution above ring coil is concave while convex distribution of magnetic field intensity is generated above concentric circles coil. Change of RX coil(s) position(s) in such



(a) Ring coil (b) Concentric circles coil

Fig. 2: Conventional coils

TABLE I: Simulated coils parameters

Parameter	**Description**	**Ring coil**	**Concentric circles coil**
N, [mm]	number of turns	5	9
r_{out}, [mm]	outer radius of coil	45	45
th, [mm]	trace height of turn	0.035	0.035
tw, [mm]	trace width of turn	0.5	1
s, [mm]	adjacent turns spacing	0.5	4

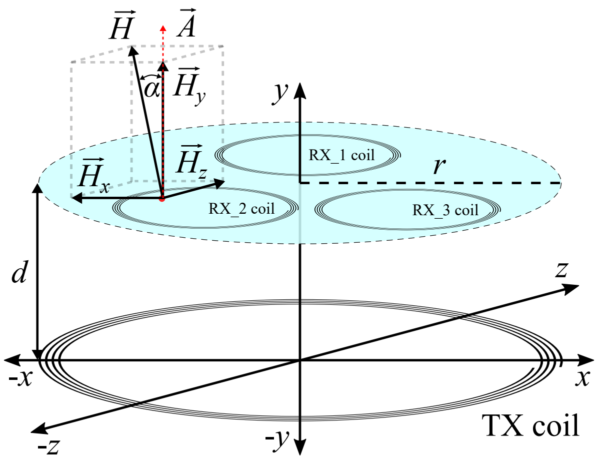


Fig. 1: Sketch of planar RIWPT

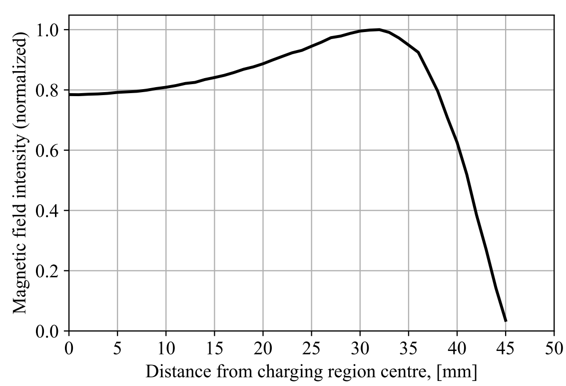


Fig. 3: Magnetic field intensity distribution (vertical component) across charging line of ring shaped coil

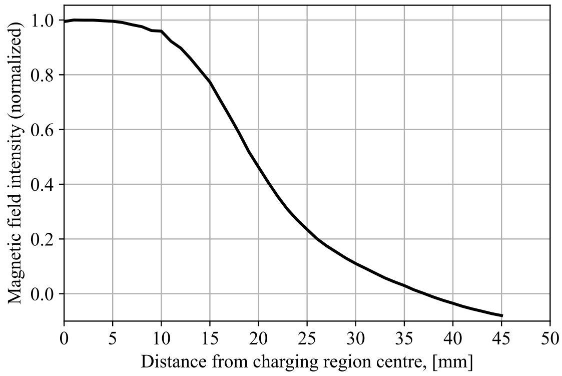


Fig. 4: Magnetic field intensity distribution (vertical component) across charging line of concetric circles sheped coil

nonhomogeneous magnetic field intensity distributions at charging plane causes change in magnetic coupling factor, k, which should be stable to keep efficiency and load power at desired level. Additionally, when fundamental resonant frequency is applied, maximum power transfer (along with 50% efficiency) is achieved at specific value of magnetic coupling factor which is called as critical coupling factor, k_c, [4], [8].

Flattening of magnetic field distribution by superposition of magnetic fields of combined outer ring coil (concave distribution) and inner concentric circles coil (convex distribution) is an innovative idea that came up in previous scientific papers, [10], [21], [22]. However, majority of proposed solutions are based on approximate position adjustment of coil turns and observing magnetic field distribution rather than executing mathematical optimization. In this paper, GA is used as a tool to find optimal design of concentric circles coil with predefined radius of outermost coil circle, r_{out}.

III. GENETIC ALGORITHM BASED OPTIMIZATION OF TX COIL

TX coil axisymmetric model is shown in the Fig. 5. Coil consists of concentric circular turns that are separated in nine equal sections. Each section consists of four turns. First section (section_1) is outermost and radii of corresponding turns are denoted as R_{11}, R_{12}, R_{13}, R_{14}, (see Fig. 5). First number in the subscript is the ordinal number of section and second number in the subscript is the ordinal number of turn in corresponding section. Following eight sections are not shown in Fig. 5, but they use the same logic to distinct remaining turns of coil. According to Fig. 5, between each turn of the coil is space denoted by s = 0.5 mm. Coil is intended to be made in PCB technology, so trace (turn) height, *th*, is set to be 0.035 mm and trace (turn) width, *tw*, is set to be 0.75 mm. Also, currents passing through turns of section_1 are labeled as I_{11}, I_{12}, I_{13}, I_{14}. Labeling currents of each section adheres to the same rule as labeling radii of turns of coil sections.

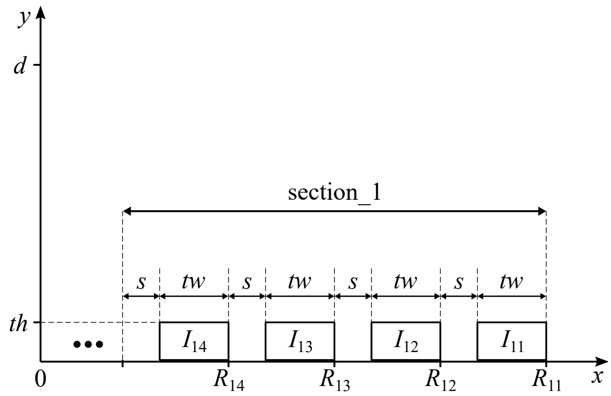


Fig. 5: Simplified representation of optimized TX coil

According to previously described model, coil is formed out of 36 turns and adjacent turns are equally spaced by 0.5 mm. However, during optimization, current of each turn could be either 0 or 1 (binary digit). If the turn current equals to zero, then that turn is actually omitted. On the other hand, if the turn current is equal to one, then corresponding turn is the part of the optimized coil. Thus, all turns that conduct current equal to one belong to coil and all turns which current is equal to zero are not taken into account and left floating.

Optimization is performed in Python-FEMM cosimulation. FEMM is used to calculate magnetic field intensity in charging line. FEMM do not have its own optimization module so it was required to work in cosimulation with other software which is compatible with FEMM. The module pyFEMM is a Python package that allows for the operation of FEMM via a library of Python functions, [26]. Thus, pyFEMM module provides creating model of coil externally from the Python thus allowing to define variables which describe coil and which are optimized (decision variables). Python library pygmo was used for optimization.

There are nearly 20 heuristic global optimization algorithms that are currently available to use in pygmo library. Genetic algorithm in pygmo library is called Simple Genetic Algorithm (SGA), and is specified as stochastic, single-objective, unconstrained and integer programming, [27]. SGA is suitable for solving optimization problem with regard to suggested coil model because there is one (single) objective of generating as large as possible homogeneous region within the charging plane. The mathematical notation of the optimization problem is as follows:

$$f(\mathbf{x}) \rightarrow \ min., \ \ \mathbf{x} \in \ \mathbb{Z} \tag{2}$$

subject to constraints:

$$\begin{aligned} c_e(\mathbf{x}) &= 0, \\ c_i(\mathbf{x}) &\leq 0. \end{aligned} \tag{3}$$

$\mathbf{x}$ is a vector of decision variables or chromosome that involves n integers. Function that is to be minimized, (2), should be specified to express objective of optimization.

In this optimization problem, equality and inequality constraints are not present, (3). For that reason, optimization problem is said to be unconstrained. Lower and upper bound of $\mathbf{x}$ are as follows:

$$0 \leq \mathbf{x} \leq 1, \quad (4)$$

that is in accordance with allowed binary value of turn current. Fitness function, (5), is used to evaluate how good the solution represented by a chromosome is, [28].

$$f(\mathbf{x}) = -(r_{hom.}/r), \quad (5)$$

where $r_{\text{hom.}}$ is a fraction of radius r that is characterized by homogeneous magnetic field intensity. Magnetic field intensity is calculated at 45 points that are placed on charging line. Distance between two adjacent points is 1 mm. Magnetic field intensity at certain point on charging line is homogeneous if the following inequallity is satisfied:

$$|\vec{H}_y| \geq 0.95 \cdot |\vec{H}_{ymax}|. \quad (6)$$

Before executing optimization, it is necessary to set SGA parameters. SGA is an algorithm from larger group of related algorithms called evolutionary algorithms (EAs). SGA imitate biological evolution in highly simplified way. Main idea of this iterative process is to keep good solutions through generations along with randomly exploring solution space to avoid stucking in local optimum. To mimic biological evolution, genetic operators used in SGA are: selection, crossover and mutation. Basic SGA parameters applied for coil optimization are listed in Table II.

SGA finds optimal solution as a coil that consists of 12 turns. Nine of turns are concentrated at the edge of coil and each adjacent turns are uniformly separated by s. That nine turns includes each turn of first two sections and outermost turn of third section. Remaining turns that form optimal coil are closer to coil center, turn with radius R_{51}, turn with radius R_{82} and turn with radius R_{83}. Therefore, optimal coil design is a specific combination of uniformly and nonuniformly separated turns.

Magnetic field intensity distribution in charging line that are 10 mm above optimaly designed coil is shown in the Fig. 6. Continuous homogeneous magnetic field intensity is generated in 66.67% of charging line length.

In comparison to conventional coils and theirs magnetic field intensity distribution, homognenous magnetic field intenisity distribution is achieved. However, in comparison with other solutions which address the same problem, this solution achieves nearly large homogeneous region, Table III.

TABLE II: SGA parameters

SGA parameters	Description	Type	Value
gen	number of generations	integer	50
pop	population size	integer	50
selection	[27]	tournament	3
crossover	[27]	exponential	n/a
cr	crossover probability	real number, cr ∈ [0,1]	0.9
mutation	[27]	polynomial	n/a
m	mutation probability	real number, m ∈ [0,1]	0.07

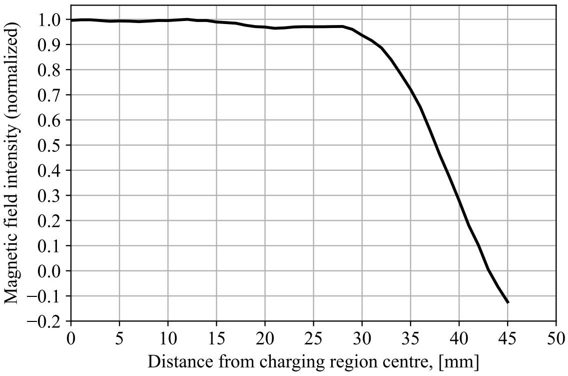


Fig. 6: Magnetic field intensity distribution (vertical component) accros charging line of optimal coil design

TABLE III: Comparison with other 2D TX coil designs

Paper	$\mathbf{H_y/H_{ymax}}$	Transfer distance, [mm]	Homogeneous region, [%]
[12]	≥ 0.8	1	∼36.0
[15]	≥ 0.8	50	∼51.8
[16]	≥ 0.904	100	∼42.3
[17]	≥ 0.7	15	∼64.0
[20]	≥ 0.928	18	∼49.0
This paper	≥ 0.95	10	∼44.4

Future plans for increasing homogneous region of optimized concentric circles coil include: parallel connection of turns which implies different current distribution than binary (but positive integer) and using both layers of PCB instead of one that is used in this paper (coil becomes 3D).

IV. Conclusion

Homogeneous magnetic field intensity in charging plane ensures stable efficiency and load power in RIWPT. In order to achieve as large as possible homogeneous region, concentric circles TX coil is optimized using SGA of pygmo library along with FEMM. Proposed coil generates homogeneous region that occupies 44.4% surface of charging plane. Such performance is comparable with other proposed coils intended for generating homogeneous region. Future goal is to enlarge homogeneous region by introducing different current distribution and utilizing PCB in terms of printing optimal coil design on both PCB sides.

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