

Optimization of Planar Spiral Coils for Wireless Power Transfer Systems Using Generalized Pattern Search Method

I. A. Zergua, N. Mohdeb, N. Ikhlef, L. Aomar, Z. Belli, H. Allag

L2EI Laboratory, Department of Electrical Engineering, University of Jijel, Algeria, mohdeb.naamane@gmail.com

Optimization of power transfer efficiency is an important way to increase the performance of a wireless power transfer system. Coil shapes have played a profound role in the performance of wireless power transfer, especially with the coupling coefficient, output power, and energy transmission. Spiral coils can provide a better coupling coefficient over various distances between the transmitter and receiver coil. Therefore, it is important to design a reasonable coil shapes to improve the transfer performance of the system. Achieving optimum coil geometry, which maximizes the transfer quality factor of WPT system, requires proper selection of optimization method. A direct search method called the generalized pattern search algorithm (GPS) was used to optimize the mutual inductance between the transmitter and the receiver coil. A GPS method was used to optimize the coil, according to the developed objective function. The procedure relies on coupling a GPS algorithm to a mathematical model to perform an automated optimization design of the WPT system. The results show the optimum geometry designed for the WPT system operating at 85 kHz, with transfer quality factor of 60.42, can achieve maximum efficiency of 96.22 %.

Index Terms—Wireless power transfer, Flat spiral coil, Coil design parameters, System performance, Optimization, Genetic algorithm, Generalized pattern search.

I. INTRODUCTION

Wireless Power Transfer (WPT) consists in transferring energy between circuits without any cables connecting them; it can be radiative or non-radiative depending on the mechanism used to transfer energy [1].

The increasing production of WPT devices and the increasing demand on them have made many enterprises and research centers looking to improve this field and overcome the obstacles they face to obtain the highest possible efficiency. Several different forms of WPT exist, including microwave, ultrasonic, capacitive coupling, inductive coupling, and light wave WPT [2],[3],[4]. The parameters affecting transmission efficiency are the frequency, the turn number of the coils, the vertical distance, the horizontal distance and the angle between the coils.

In order to improve the transfer quality factor of the coil, it is necessary to increase the ratio of mutual inductance to resistance of the coil. High transfer quality factor can be achieved by determining the optimal parameters using a design algorithm of circular planar coil. This work proposes a comprehensive single-objective optimization design of a WPT which the procedure relies on generalized pattern search (PS) method [5],[6] to an analytical model to perform an automated optimization design of the system. By comparing and analyzing simulation results, output power and transmission efficiency of WPT system with designated coil structure are improved.

II. SYSTEM MODELING AND FORMULATION

The choice of the type of compensation is based on several factors, such as the type and dimension of load, fixed or moving supply, etc. The SS compensation network is considered for this optimization example. SS compensation network is widely adopted because it is simple and easy to tune [1]. Fig.1 shows the lumped-element circuit model of a WPT system based on resonant magnetic coupling between two electrically small

loops. The variable M denotes the mutual inductance between two loops.

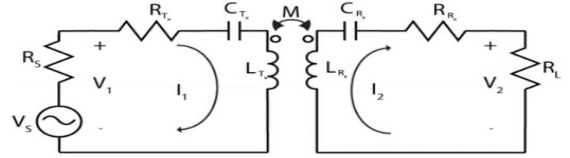


Fig.1. Equivalent circuit model of SS compensated topology

Using Kirchhoff's voltage law, the system can be obtained as [4],[5],[6]:

$$\begin{bmatrix} Z_{Tx} & j\omega_0 M \\ j\omega_0 M & Z_{Rx} + R_L \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} V_1 \\ 0 \end{bmatrix} \quad (1)$$

$$Z_{Tx,Rx} = j\omega_0 L_{Tx,Rx} + \left(\frac{1}{j\omega_0 C_{Tx,Rx}} \right) + R_{Tx,Rx} \quad (2)$$

Where V_1 is the RMS voltage of the HF source with a fundamental frequency ω , and $Z_{Tx,Rx}$ are the impedances of transmitter and receiver resonators respectively.

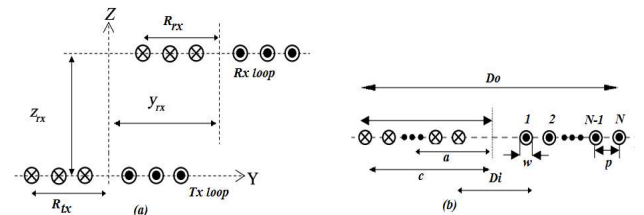


Fig.2 Geometry of a WPT system with circular spiral: a) filamentary circular coil arrangement, b) approximation of the flat spiral coil

Fig.2 shows geometry of a WPT system with circular spiral shaped T_x and R_x coils. Axial and radial separation between T_x and R_x are z_{rx} and y_{rx} respectively. Mutual inductance between circular coils can be calculated using filament method by modelling the coil as a set of filamentary circular loops [3]:

$$M_{i,j} = \frac{\mu_0}{\pi} \sqrt{r_{txi} r_{rxj}} \int_0^\pi \frac{(\cos(\theta) - \frac{d}{r_{rxj}} \cos(\phi)) \psi(m)}{\sqrt{V^3}} d\phi \quad (3)$$

The efficiency of the WPT system can be derived at resonance frequency as follows [2]:

$$PTE_{out,\omega_0} = \frac{\left(\frac{\omega_0 M}{\sqrt{R_{Rx} R_{Tx}}}\right)^2}{\left(1 + \left(\frac{\omega_0 M}{\sqrt{R_{Rx} R_{Tx}}}\right)^2 + \frac{R_L}{R_{Rx}}\right)} \frac{\frac{R_L}{R_{Rx}}}{\left(1 + \frac{R_L}{R_{Rx}}\right)} \quad (4)$$

Where $T_Q = \frac{\omega_0 M}{\sqrt{R_{Rx} R_{Tx}}}$ represents the transfer quality factor.

III. RESULTS

The parameters that will be examined are coil separation, coil size, pitch and wire diameter. For our implementation, D_o is limited to 400 mm for primary and secondary coil, and should be emphasized that the method will design the optimized coil with inputs constraints, but the maximum efficiency depends on the limits and constraints as listed in Table I.

TABLE I
SPECIFICATION OF THE PROTOTYPED GEOMETRY

Parameter	Description	Value	
		Min	Max
f	Excitation frequency (kHz)	85	
R_L	Loading resistance (Ω)	4	
V	Output Voltage (V)	48	
z_{rx}	Coil Separation (mm)	100	
r_{rxo}, r_{txo}	Inner radius of the primary coils (mm)	120	180
$w_{1,2}$	Radius of the wire coil (mm)	1.8	2.9
$p_{1,2}$	Spacing between turns (mm)	0	2.5

Quality factor variation with respect to the design parameters is examined in this section. Fig.3 shows quality factor variation at different inner radius.

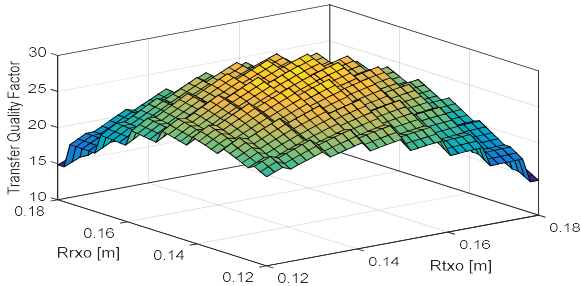


Fig.3 Effect of inner radius on the transfer factor quality

Geometrical optimization is used to determine the transmitter and receiver coils dimensions. The fitness function is defined as follows:

$$\begin{cases} \text{maximize} : f(\theta) = \frac{\omega_0 M(x)}{\sqrt{R_{Rx} R_{Tx}}} \\ x = [p_1, p_2, w_1, w_2, r_{txo}, r_{rxo}] \end{cases} \quad (5)$$

Generalized Pattern search method is a class of direct search method for solving nonlinear optimization problems. The generalized pattern search algorithm proceeds by figuring a succession of point that isn't near to the best point. By comparison, the PS algorithm requires on the order of less function calls, making its run time negligible compared to the genetic algorithm. The results of convergence are shown in Table II. The GA also required more time for finding the best solution, showing that power splitting is a computationally expensive process for this algorithm. Fig.4 illustrates the evolution of fitness function through generations. It can be seen from the convergence curves of the two methods shown in Fig. 5 that the pattern search method has best fitness function.

TABLE II
RESULTS OF OPTIMIZATION METHOD

	Parameters (mm)					
	p1	p2	w1	w2	r _{txo}	r _{rxo}
PS	0.4	0.2	2.4	2.8	155	145.4
GA	0.1	0.6	2.7	2.5	143.4	151.2

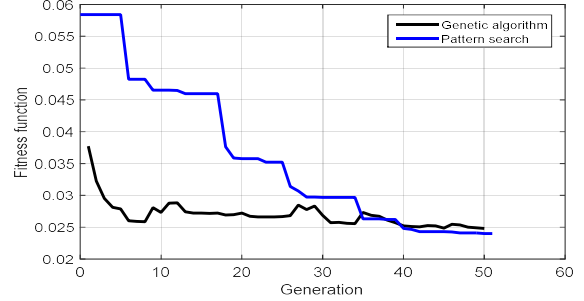


Fig.4 Convergence curve of genetic algorithm and pattern search

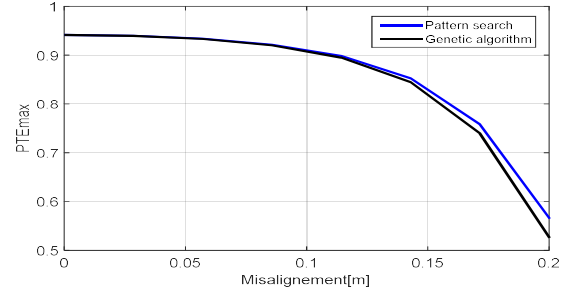


Fig.5 PTE_{max} Performance curve versus the variation of the misalignment

IV. CONCLUSION

Effects of coil shapes for the WPT system were studied in-depth here. Automated optimization design of T_x and R_x coil pairs is considered to transfer quality factor for SS compensated inductive power transfer system. In order to select the most favorable numerical value for T_Q a genetic algorithm (GA) or generalized pattern search (PS) method are introduced which maximizes T_Q based on the WPT system application and physical size limitations. The results show that the method of determining the general characteristics of a coil and then optimizing the design parameters can obtain a higher transfer quality factor than the classical method of T_x and R_x coil pairs with equal turn spacing.

REFERENCES

- [1] A. Kuperman, "Additional two-capacitor basic compensation topologies for resonant inductive WPT links". IEEE Trans. Power Deliv. Vol.35, pp.2568-2570, 2020.
- [2] A. Ibrahim and M. Kiani, "A figure-of-merit for design and optimization of inductive power transmission links for millimeter-sized biomedical implants," IEEE Trans. Biomed. Circuits Syst, Vol. 10, pp.1100-1111, Dec. 2016.
- [3] Z. Zhang, H. Pang, A. Georgiadis, C. Cecati, "Wireless power transfer-An overview". IEEE Trans. Ind. Electron. Vol. 66, pp.1044-1058, 2019.
- [4] N. Mohdeb, "Comparative study of circular flat spiral coils structure effect on magnetic resonance wireless power transfer performance", Progress In Electromagnetics Research M, Vol.94, 119-129, 2020.
- [5] C. Audet, J. E. Dennis, "Analysis of generalized pattern searches", SIAM J. Optim, Vol.13, pp. 889-903, 2003.
- [6] F. Glover, G.A. Kochenberger, "Handbook of metaheuristics". Boston: Kluwer Academic Publishers, 2003.