E3S Web of Conferences 351, 01063 (2022) https://doi.org/10.1051/e3sconf/202235101063
ICIES'22

Optimal design of inductive coupled coils for biomedical implants using metaheuristic techniques

OUACHA Brahim*, BOUYGHF Hamid, and NAHID Mohammed

SIB Laboratory Faculty of Sciences and Techniques Mohammedia, University Hassan II of Casablanca, Morocco.

Abstract. Powering implanted biomedical devices (IMDs) and sensors is a major obstacle for researchers in the microelectronics field. Such as the problem of miniaturization, increasing the distance between the external part (TX) and the internal part (RX), and the improvement of the power transfer efficiency (PTE), ... The purpose of this article is to compare two strategies for optimizing component characteristics for a wireless energy transfer system (coupling of two coils), based on the new Figure-of-Merit (FoM) or iterative procedure (IP), and genetic algorithm (GA), in order to have a power transfer efficiency equal to 15% and 94.18 % respectively for a separation distance d = 12cm.

1 Introduction

Wireless Power Transfer (WPT) has seen a great evolution in recent years. As it spreads in many areas, is used in the transport sector, in the field of consumer electronics applications, in devices implantable medical (IMD). Systems WPT are used too in LED lighting, underwater detection and military defense systems [1]. We are interested in the application to biomedical devices such as powering the implantable biomedical devices is one of the important factors of the implantable biomedical devices. There are several methods to feed implanted biomedical chips such as capacitive coupling, inductive coupling.... inductive coupling is the most used in the biomedical field because it is based on the magnetic field between the emitting part (TX) and the receiving part (RX) [2]. The TX transmitter part located outside the human body, on the other hand the TX receiver part located inside. Inductive coupling is the most used method in powering biomedical implants, thanks to its low frequency and its transfer of energy in all directions [3][4]. Microelectronic components implanted in patients' bodies have several challenges, such as implant miniaturization. Reducing the surface area occupied by implanted devices amounts to optimizing the geometric parameters. In this paper, we propose an improvement of PTE and miniaturized the dimensions of the two-coupled coils by using a genetic algorithm. Such as to optimize the geometric parameters of both part of the inductive coupling system. The structure of this document is as follows: In section two we present the related works, and in section three we give a brief theoretical background about inductive coupling. In section four proposed the contribution and our proposal to improve the PTE between two coils. Finally, in the section five we explain and discuss the different results obtained, and a conclusion with perspectives is given in the section six.

2 Related works

the optimization of the geometric parameters of the two-coils of the wireless energy transfer system (inductive coupling) can be done by several methods, such as the Finite Element Method (FEM), Convolutional Neural Network (CNN), and also meta heuristic algorithms (ABC, PSO, GA, ...). In [5], the authors proposed another factor, Figure of Merit (FoM) based on iterative procedure, which meets both the PTE and the PDL. Their results demonstrated the IP made it possible to improve the power transfer efficiency for an optimized inductive link, i.e., 72.5% against 44%, using repeating coils. The authors in [6] present another method to obtain a high PTE, of which they add the other auxiliary repeater coils in order to increase the distance between the emitting coil and the implanted coil and the PTE. Otherwise, multiple methods of enhancing PTE as in [7], offered a novel method for optimizing and characterizing rectangular coils, which are most used in inductively coupled systems. As in this study achieved a PTE of 46.4% with a distance of 10mm.

3 Theoretical background

3.1 Inductive link modeling

Figure1 shows the simplified structure of two-coils inductive link between the TX (transmitter) and RX (receiver) separated by Air and Skin. Such that the primary and secondary coils are labeled L1 and L2, respectively, (R1, R2) the parasitic resistances of the two coils respectively. RL is the load.

* Corresponding author: brahim.ouacha-etu@etu.univh2c.ma

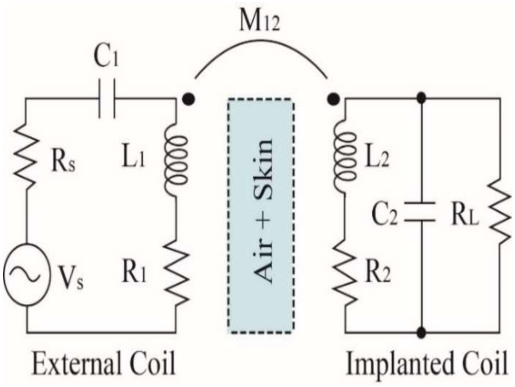

Fig. 1. Equivalent diagram of inductive coupling with two-coils.

The size of the two parts of the energy transfer system used and the distance between them is one of the most intriguing aspects for the system's design., in order to have an efficient power transmission, from the source to the load implanted in patient body [8]. The PTE can be calculated by the ratio between input and the power given to the load is known as output power (PDL).

$$\text{PTE} = \frac{P_{out}}{P_{in}} \quad (1)$$

Where:

P_{in}: Input power,

P_{out}: Output power

To improve the power transfer efficiency (PTE), both parts of the system should be configured by the same resonant frequency [8], and maximize the coupling and quality factors, because PTE is depending to Q and k, such as:

$$\text{PTE}=\frac{k^2_{12}Q_1Q_{2L}}{1+k^2_{12}Q_1Q_{2L}} * \frac{Q_{2L}}{Q_L} \quad (2)$$

$$Q_1 = \frac{wL_1}{R_1},\ Q_2 = \frac{wL_2}{R_2},\ Q_{2L} = \frac{Q_LQ_2}{Q_L+Q_2},\ Q_L = \frac{R_L}{wL_2};$$
$$k_{12} = \frac{M_{12}}{\sqrt{L_1L_2}};$$

The power transfer efficiency equation shows that it is independent of the source resistance Rs and solely depends on quality and coupling factors.

3.2 Self and Mutual inductances

Electromagnetic induction is a physical phenomenon leading to the appearance of an electromotive force in an electrical conductor subjected to a variable magnetic field flux. This electromotive force can generate an electric current in the conductor. This current is related to the two parts of system(L_1, L_2) [9][10].

For the square coil, the inductance can be calculated using the following formula:

$$\text{L} = \frac{1.27.\mu_0.n^2.d_{avg}}{2}\left[l\left(\frac{2.07}{\varphi}\right) + 0.18\varphi + 0.13\varphi^2\right] \quad (3)$$

$$\varphi = \frac{d_{out}-d_{in}}{d_{out}+d_{in}};\ d_{avg} = \frac{d_{out}+d_{in}}{2}$$

Where;

n: number of turns

l: length of conductor

dout: outer diameter

din: inner diameter

φ: form factor

The same for the mutual inductance it is a function of the inductances of the two-coupled coils and of the coupling factor as it shows in the following equation:

$$M_{12} = k_{12}\sqrt{L_1L_2} \quad (4)$$

It can be seen that the proper and mutual inductance of the two-coupled coils depend on the shape and characteristics of the coils shown in figure 2 below.

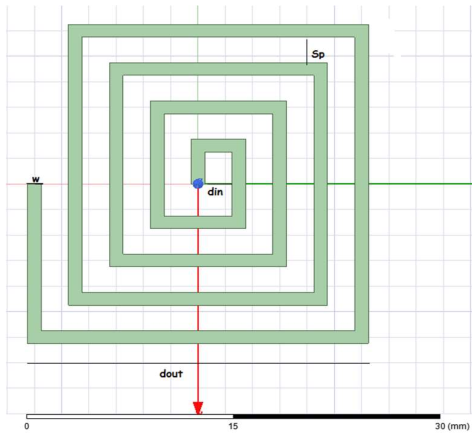

Fig.2. Geometry of a square shaped coil.

The geometric parameters characterizing the inductance in a square spiral are the number of turns (n), track width (w), track spacing (S_p) and(d_{out}) is the outer diameter. (d_{in}) Is the inner diameter of inductor. In addition, they are related by the following equations:

$$d_{out} = d_{in} + 2 * n * w + 2 * (n-1) * S_p \quad (5)$$

And ;

$$l = 4 * n * \left(d_{out} - (n-1) * S_p - n * w\right) - S_p \quad (6)$$

4 Proposed method

Most researchers focus on maximizing Power Transfer Efficiency. metaheuristic algorithms are the most used for the optimization of inductance parameters [11][12].

In this work, to optimize the geometrical parameters of the two-coupled coils, we proposed to apply the genetic algorithm (GA) which carries out searches in a random way within an environment or space specified for possible solutions [13].

Genetic algorithms (GA) have a multiple genetic operator:

Selection: It steers the search to the parts of the search space where the best solutions are most likely to be found.

Crossover: By mixing the information in the parents, it creates new individuals.

Mutation: It's used on a low-probability population of kids. We employed the Gaussian mutation with a probability pm = 0.25 in order to maintain the diversity of the children's population.

The genetic algorithm follows an operating procedure as shown in the figure 3. This iterative algorithm quickly converges to the optimal solution as it shows in figure 4; it converges from 200 iterations.

```
Make use of the PTE model (2)
Calculate the fitness factor.
Begin
Set up the pop (0)
     While k<max_gen do
               Evaluate pop(k) using fitness function
               Select New-pop from pop(k)
               Applying genetic operators (cross & mutation) to New-pop
               K=k+1
     End
Generate the best individual ()
End
```

Fig. 3. The structure of the GA.

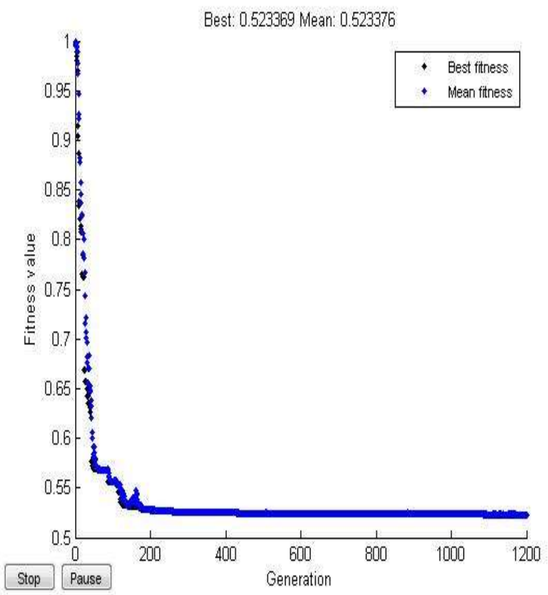

Fig.4. Inverse of efficiency (PTE) versus generation by applying GA.

5 Results and discussion

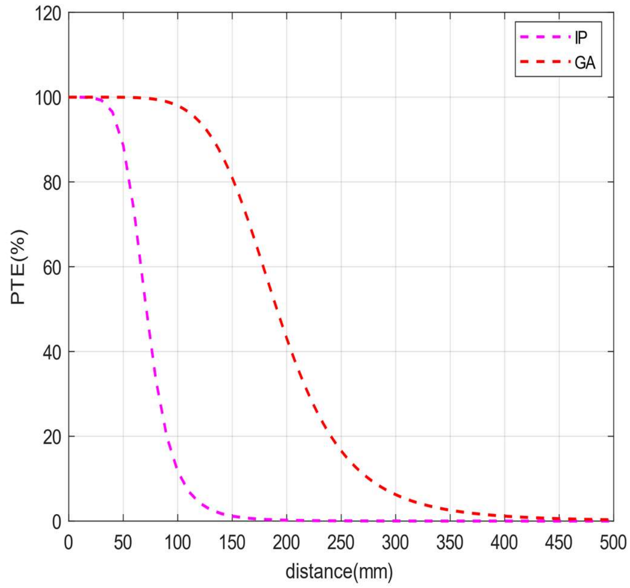

Fig.5. Numerical efficiency versus distance.

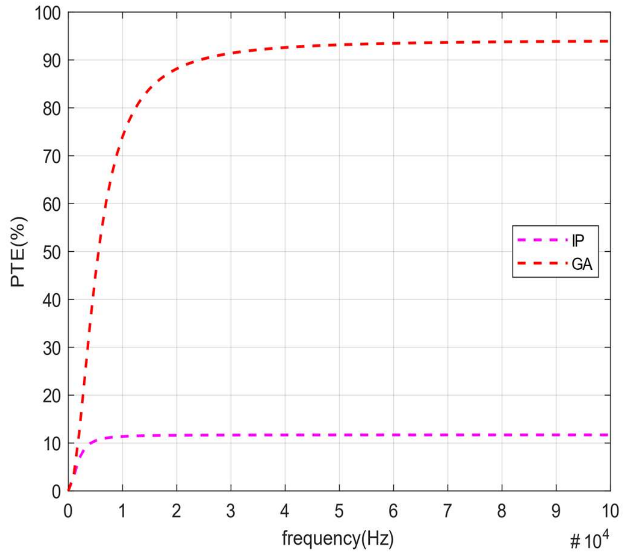

Fig.6. Numerical efficiency versus frequency.

The inductive coupling between two coils optimized by the genetic algorithm is simulated using MATLAB software. The obtained results are shown in figures 5 and 6, such that the PTE increases as a function of the frequency in order to have a maximum value equal to 94.18% at the resonant frequency 13.56MHz, also, the best frequency value derived using the genetic algorithm approach is included in the ISM recommended interval. The FOM approach converges to around 15% accuracy because for a fairly high frequency we fall on several factors of loss the energy, such as the effect of skin or proximity. And decreases as a function of the separation distance between two coupled coils because the coupling factor diminishes as the distance between the two coils grows.

the optimum values of the geometric parameters of the two parts of the energy transfer system obtained by GA are given in Table 1.

Table 1. Specifications results from FoM and GA based optimization

Parameters	Using FoM	Using GA
$dout_1$	36mm	49.77mm
$dout_2$	10mm	5.0984mm
w_1	1.15mm	2mm
w_2	0.51mm	0.0501mm
Sp_1	100µm	0.6mm
Sp_2	100µm	0.0101mm
n_1	10	9
n_2	1	2
d	12cm	12cm
f_0	13.56MHz	13.56MHz
PTE	15%	94.18%

6 Conclusion

The genetic algorithm was employed in this study to find the best values of the geometric parameters of the coils (external and implanted) and the distance between them.

This technique was applied to maximize the power transfer efficiency between two-coupled coils; the obtained results have shown the PTE have been improved. As a future work, we well be invest on improving more the PTE at large distance and miniaturize the dimension of coils. Also, low resonance frequency. Also, based on meta heuristic algorithms.

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