Determination of the coupling-loss distance between the inductive coils in a transcutaneous energy transfer system

A.A. Danilov, K.O. Gurov
JSC ZITC, Zelenograd, Russia
Contact: constantinegurov@yandex.ru

Introduction

Improving the methods of power supply is one of the most important areas for implantable medical devices (IMD) development [1], [2]. Wireless energy transfer by means of inductive coupling represents one of the possible solution. This technology is currently the main method of feeding cochlear implants [3], [4] and of the spinal cord stimulators [5], [6]. The prospective areas of application include energy supply systems for mechanical support of blood circulation [2], [7], visual prostheses [8], [9] and active orthopedic implants [10].

There are areas of research on transcutaneous energy transfer using inductive coupling, an example is the development of formal design and optimization methods developing to this day [11]. Important for solving problems in the implementation of such methods is to ensure the stability of energy transfer, when the receiving and transmitting coils are offset relative to each other, as well as increasing the efficiency of energy transmission [12], [13].

The formal rules for determining the boundary and initial conditions must be defined in order to optimize the geometry of the coils. One of these rules can be the determination of the optimal distribution of the turns in the inductive coil, at which the coupling between them is stable, and the energy transfer efficiency is sufficient for power supply of the device.

Materials and Methods

One of the key problems in the use of inductive coupling for transcutaneous energy transfer is accounting for and compensating for the effect of coil bias on the system output characteristics [1]. Misalignments are usually divided into axial (d, change in the longitudinal distance between the coils), lateral (ρ, misalignments of the coils in a plane perpendicular to the axis of the receiving coil) and angular (φ, change in the angle between the axes of the coils). In this case, the greatest influence on the system characteristics is caused by lateral misalignments, since the magnitude of the axial and angular misalignments is to a considerable extent limited by the system geometry. Numerical simulation of the energy transmission system allows to investigate this problem with the aim of solving it. With the help performed calculations, it is possible to realize the energy transfer system with various geometrical parameters of the coil pair and their misalignments.

In the course of theoretical study, points of zero mutual inductance (M_{zero}) were located. In this case, both the axial misalignments and the geometric configurations of the coil couple were changed. Thus, using the numerical simulation, the graphs shown in figures 1, 3, 5 were obtained.

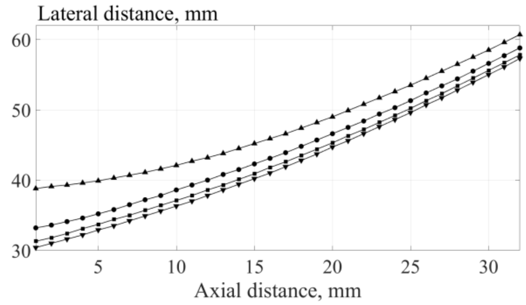

Figure 1: The ratio of axial to lateral misalignments for points of zero mutual inductance as a function of one- (▲), two- (•), three- (■) and four-turn (▼) coils. Fixed outer diameter 50 mm, internal diameter 50 ... 25 ... 16.6 ... 12.5 mm, winding pitch 0 ... 12.5 ... 8.3 ... 6.25 mm, the number of revolutions is 1 ... 2 ... 3 ... 4, respectively.

Figures 1 and 3 shows a graphs of the dependence of the axial misalignments of the lateral for the zero point of the mutual inductance. The calculation was performed for four symmetrical coil couple with a value of the number of turns from 1 to 4. The outer diameter (D_{out}) was fixed at a value of 50 mm (Fig. 1) or 100 mm (Fig. 3) for all four simulated coils. The pitch between turns was chosen in such a way that it was equal to D_{out} / 2n, where n is the number of turns.

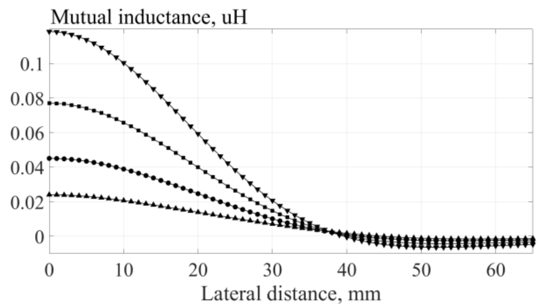

Figure 2: Mutual inductance versus lateral misalignments. Fixed outer diameter 50 mm, internal diameter 50 ... 25 ... 16.6 ... 12.5 mm, winding pitch 0 ... 12.5 ... 8.3 ... 6.25 mm, the number of turns 1 (▲) ... 2 (•) ... 3(■) ... 4(▼), respectively. Axial misalignments 15 mm.

In the course of another theoretical study, the mutual inductance was found to depend on lateral misalignments.

In this case, the point of maximum (M_{max}) (the lateral misalignments is zero) and the point of zero mutual inductance (M_{zero}) were analyzed. This analysis is presented in figures 2, 4 and 6.

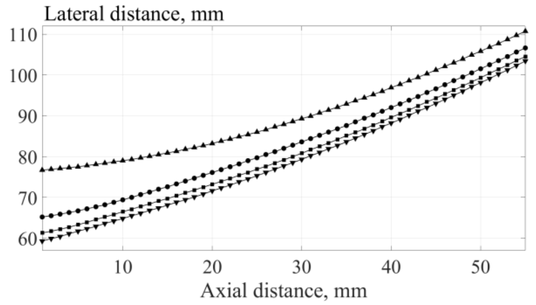

Figure 3: The ratio of axial to lateral misalignments for points of zero mutual inductance as a function of one- (▲), two- (•), three- (■) and four-turn (▼) coils. Fixed outer diameter 100 mm, internal diameter 100 ... 50 ... 33.3 ... 25 mm, winding pitch 0 ... 25 ... 16.6 ... 12.5 mm, the number of revolutions is 1 ... 2 ... 3 ... 4, respectively.

Figures 2 and 4 show the graphs of the mutual inductance versus the lateral misalignments of a symmetrical coil couple. The calculation was carried out for four symmetrical coils with a speed of 1 to 4. The outer diameter (D_{out}) was fixed at a value of 50 mm (Fig. 2) or 100 mm (Fig. 4) for all four simulated coils. The pitch between the turns was chosen in such a way that it was equal to D_{out} / 2n, where n is the number of turns. The axial misalignments was selected taking into account the average skin thickness between the inductance coils in the energy transfer system, which is 15 mm.

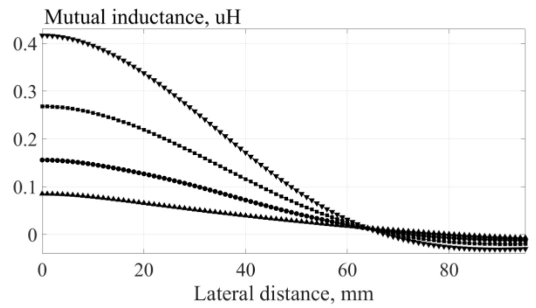

Figure 4: Mutual inductance versus lateral misalignments. Fixed outer diameter 100 mm, internal diameter 100 ... 50 ... 33.3 ... 25 mm, winding pitch 0 ... 25 ... 16.6 ... 12.5 mm, the number of turns 1 (▲) ... 2 (•) ... 3(■) ... 4(▼), respectively. Axial misalignments 15 mm.

The last study was the numerical simulation of four coil couples with a fixed outer diameter of 50 mm, and the number of turns 2. The value of the internal diameter varies from 30 to 15 mm (30 ... 25 ... 20 ... 15 mm), the pitch between the turns, respectively changed from 2.5 mm (10 ... 12.5 ... 15 ... 17.5 mm). The graphs obtained from the calculations are shown in figures 5 (the ratio of the zero point of the mutual inductance to the axial misalignments) and 6 (the ratio of the mutual inductance to the lateral misalignments).

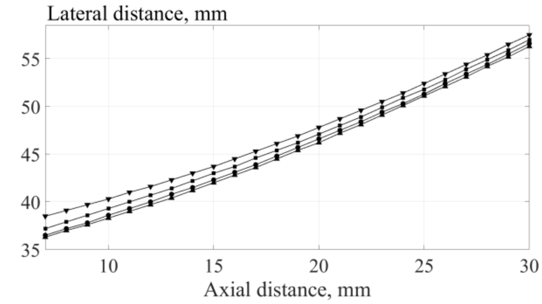

Figure 5: The ratio of axial to lateral misalignments for points of zero mutual inductance. Fixed outer diameter 50 mm, internal diameter 30(▲) ... 25(•) ... 20 (■) ... 15(▼) mm, winding pitch 10 ... 12.5 ... 15 ... 17.5 mm and fixed the number of turns 2.

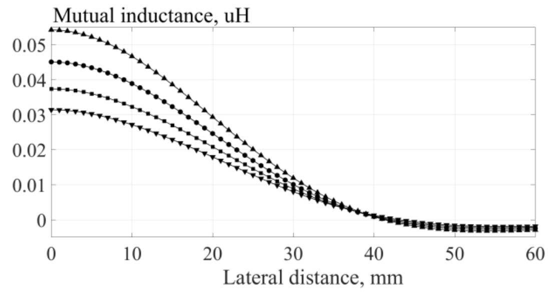

Figure 6: Mutual inductance versus lateral misalignments. Fixed outer diameter 50 mm, internal diameter 30(▲) ... 25(•) ... 20 (■) ... 15(▼) mm, winding pitch 10 ... 12.5 ... 15 ... 17.5 mm and fixed the number of turns 2. Axial misalignments 15 mm.

Results

The main characteristics of a couple coil, which can change when using the design algorithm, include the outer and inner diameters, as well as the winding pitch / number of turns. According to the graph shown in figure 2, it is seen that as the value of n increases in the coil, the zero point of the mutual inductance shifts to the left closer to zero ρ. So the lateral misalignment at M_{zero} for a one-turn coil is 44.6 mm, and for a four-turn this value drops to 39.6 mm, with a fixed D_{out} of 50 mm. Thus, the zero point shift was changed by 11% from the value for a one-turn coil. It follows that the coil with a smaller number of turns has a greater stability, in terms of loss of coupling. As shown in figure 1, this decrease with increasing n is exponential.

A similar exponential dependence (Fig. 3) is observed with an increase in D_{out} up to 100 mm. The lateral misalignment at M_{zero} increases in 1.65 ... 1.8 times, in comparison with coils, whose outer diameter is 50 mm. Figure 4 shows that ρ at a zero point of the mutual inductance for a one-turn coil is 80.1 mm, and for a four-turn coil this value drops to 65.5 mm, with a fixed D_{out} of 100 mm. Thus, the M_{zero} shift has changed by 18% from the value for a one-turn coil. The axial misalignments of 15 mm for the numerical simulation of the graphs presented in figures 2 and 4 was chosen as the average value of the thickness of the skin layer between the coils in the energy transfer system.

It should be noted that the curves for lateral misalignments at the zero point of mutual inductance have a stable linear character after $d \approx D_{out} / 2.5$ (Fig. 1, 3).

The drop M_{max} with decreasing n from 4 to 1 occurred from value 0.4165 to 0.0848 (Fig. 4), at D_{out} 100 mm. With D_{out} 50 mm, the drop M_{max} with decreasing n from 4 to 1 occurred from value 0.1184 to 0.0240 (Fig. 2). In both cases, the maximum value of the mutual inductance decreased by approximately 80%. In this case, M_{max} (D_{out} = 100 mm) on 71% or 3.5 times larger than M_{max} (D_{out} = 50 mm). This difference is explained by the length of the wire needed to fill two coils with the same number of turns, but differing D_{out}. Because of the difference in the length of the wire, the self-inductance of the coil with a large D_{out} is obtained more, and, consequently, the mutual inductance will increase. This drop in M_{max} with decreasing D_{out} can be reduced by increasing the number of turns close to the outer edge.

Adjustment of the M_{max} and M_{zero} values can be performed by changing the pitch between turns. However, the smaller the pitch the more difficult it is to adjust the values due to the exponential fall (Fig. 5).

As shown in figure 6, the location of the turns closer to the outer edge of the coil allows to increase M_{max}. The increase in the value of M_{max} is 42% (from 0.0542 to 0.0314), the diameter of the inner turn of 30 mm and 15 mm, respectively, with a fixed D_{out} of 50 mm and the number of turns 2. However, in this case, the location of the turns, a large increase in M_{max} leads to a slight decrease in ρ at M_{zero} by 4% (from 43.1 mm to 41.3 mm).

Discussion

Increased number of turns lead to reducing the stability of energy transfer (Fig. 2, 4). Moreover, such a decrease in M_{zero} to zero value of lateral displacement occurs according to the exponential dependence even with an increase in the outer diameter of the coil (Fig. 1, 3). It is assumed that in order to achieve greater stability of energy transfer, it is necessary to reduce the number of turns in the coil.

For coils with the same number of turns D_{out} and M_{max} are positively associated (Fig. 4): drops in D_{out} lead to drops in M_{max}. This is due to the difference in the length of the wire, and, consequently, of the intrinsic inductance, which affects M_{max}. It is possible to reduce the drop of the M_{max} by increasing the length of the wire in the coil (Fig. 5, 6).This is achieved by increasing the winding density of the wire from the inner to the outer edge of the coil while the original number of turns keeps constant.

Conclusions

With the help performed calculations, various configurations of coils were analyzed to determine their optimal geometry. It was found that increasing the number of turns in the symmetrical coils leads to the shift of the zero point of mutual inductance is to the zero value of lateral misalignment. Such a shift occurs on an exponential curve and with an increase in the outer diameter of the coil an exponential shift of the zero point is also observed, however it has large lateral misalignment values.

The difference in the values of the maximum mutual inductances with a fixed number of turns, but with a different external diameter, results from the length of the wire necessary to fill two coils with the same number of turns.

It should be noted that the curves for lateral misalignments at the zero point of mutual inductance have a stable linear character after $d \approx D_{out} / 2.5$.

Adjustment of the M_{max} and M_{zero} values can be performed by changing the pitch between turns. However, the smaller the pitch the more difficult it is to adjust the values due to the exponential fall.

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