Design strategy of displacement-tolerant inductive powering unit for high-power implantable medical devices

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Introduction

Development of a wireless powering technologies for implantable medical devices (IMD) is a hot point in modern biomedical engineering [1], [2]. Inductive powering is most common options for transcutaneous energy transfer [3]. Moreover, in the case of IMD with relatively high energy consumption (>0.1 W) it is the only possible solution [4].

In order to achieve high level of the transmitted power it is necessary to use relatively low frequencies, at about 0.1...10 MHz [5]. In this case losses due to energy absorption in tissue is relatively low, less than 5%. It helps to achieve greater energy transfer efficiency, but, more importantly, it largely reduces tissue heating. On the other hand, choice of low operating frequency involve choice of the relatively big transmitter and receiver. Flat pancake coils with a diameter of 5...10 cm is a common solution [5]-[9]. Energy transfer distance is in the 5...30 mm range [6], [8]. Since the size of the coils is greater than the energy transfer distance, the time-varying magnetic field, generated by primary coil, is highly non-uniform in the secondary coil plane. At the same time, dynamic environment is specific for wireless powering of an IMD [3]. Patient movements, implant migration and postoperative edema causes significant variations in a coils relative position [10]. It leads to changes in coil coupling and, consequently, in a load power. And it should be emphasized that coil movements may cause drop as well as the growth of the load power level [11]. Thus, potential impact of displacement may involve device failure as well as tissue overheating.

That said, it is an urgent and difficult task to design displacement-tolerant inductive powering unit (IPU) for high-power IMDs. In this paper we will describe our design approach and give some suggestions based on the results of numerical modeling.

Overview of methods for stabilization of an IPU output characteristics

Generally speaking, with respect to their causes all displacements fall in the three distinct categories [10]:

– *slow irregular* (displacements, associated with implant migrations or postoperative edema);

– *fast irregular* (displacements, associated with the patient movements such as changing position from sitting down to lying and so on);

– *fast regular* (displacements, associated with the patient walking or breathing).

From the geometrical point of view displacements may be divided in following manner (fig. 1):

– *axial* (*d*, e.g., changes of distance between the coils centers across axis of the receiving coil),

– *lateral* (ρ, changes of distance between the coils centers in a plane perpendicular to the axis of the receiving coil)

– *angular* (φ, changes in the angle between the axises of the coils);

– *rotational* (ψ, changes in the solid angle with the vertex at the center of the receiving coil).

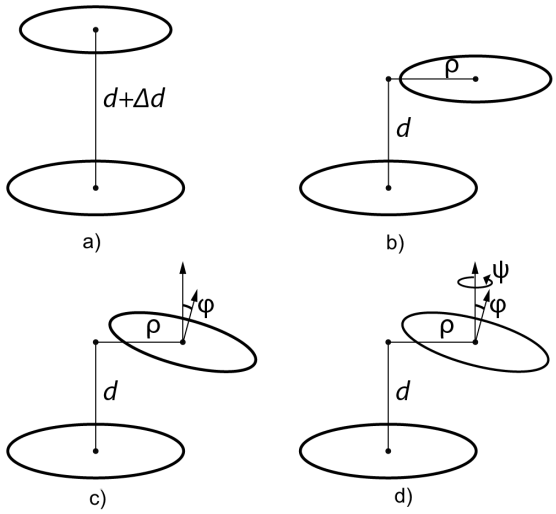

Figure 1: Axial (a), lateral (b), angular (c) and rotational (d) displacements of the coils [10]

There are several methods to deal with misalignments problem. Such methods can be described as direct and indirect. Direct methods are those which imply certain means for preventing misalignments and/or correcting coils positions.

The mound-shape coating of an implanted coil was historically first method proposed for the solution of a misalignment problem [5]. In this case external (transmitting) pancake coil must have a relatively big gap at the center in order to be be placed at the artificial bulge on the skun surface. This method was used in the LVD-2000 LionHeart system [12] – first ever ventricular assist device with inductive powering, which was approved for clinical trials – and is still considered as a feasible option [7]. It can help to reduce lateral misalignments, but it can't compensate effect of axial, angular and rotational displacements. Moreover, it pose significant restrictions on the shape of the coils, which is not optimal from the physical point of view.

Coils position may also be fixed by means of permanent magnets, which is placed at the center of both coils [13]. Such a method is common for cochlear implants. In general, it has shortcomings similar to those which are associated with the use of a mound-shape coating of an implanted coil. Moreover, magnets represents a serious problem in the case of magneto-resonance imaging of a patient, and this problem can be overcome only partially [14]. Finally, magnets can be effective only in the case of a relatively motionless inplantation point, e.g. when coils are placed at the head of a patient.

Another direct approach is based on the detection of an implanted coil position [15], [16]. If one knows the relative position of implanted and external coils, it is possible to align them manually. This method can help in the case of lateral misalignment, which are associated with implant migration (slow irregular misalignment) or changing patient's body position (fast irregular misalignment). It is not possible to use such an aprroach in the case of axial misalignments or fast regular movements.

Indirect methods fall into two distinctive categories: those which imply desensitizing of inductive link and those which imply tuning of the link (e,.g., changing source voltage or operating frequency) in order to achive desirable output charactersitics (e.g., load power) for a given coil position.

Simplest way of desensitizing is a geometric method. One can use transmitting coil with the external radius R_{Te} somewhat bigger than the external radius of receiving coil R_{Re}, and internal radius of transmitting coil R_{Ti} equal all little bit bigger than R_{Re} [8]. In this case lateral misalignment up to $\rho=R_{Te}-R_{Re}$ can be tolerated.

Another technique is known as a "stagger tuning" [17]. It is based on the so-called freqeunecy splitting [18], [19]. This effect occurs when the coupling between coils is relatively strong, or, in other words, when coils is relatively close to each other. In this case load-power have two (instead of one) peaks which correspond to two different operating frequencies (fig. 2). So, if one deliberately chose to operate in the strong-coupling region at the predermined (fixed) frequency, stable output for changing coils positions can be achieved at the cost of a decrease in the load power.

Even more stable output can be achived if one tracks resonant frequency in the case of the strong coupling [19], [20]. In the case of a frequency tracking load power is higher than in the case of a stagger tuning, but it still lower than in the case of critical coupling (fig. 3).

Design strategy

It can be said that all existing methods do not provide the universal solution of the stabilization problem. The complex nature of the misalignments and significant geometric differences made simple solution impossible. Thus, design procedure for IPU must be based on a method which takes into account several key variables.

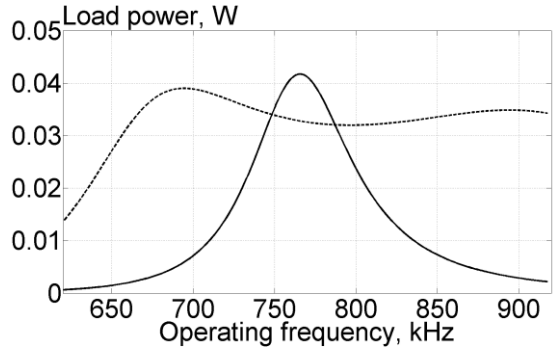

Figure 2: Load power as a function of operating frequency for a weak (solid line) and strong (dashed line) coupling

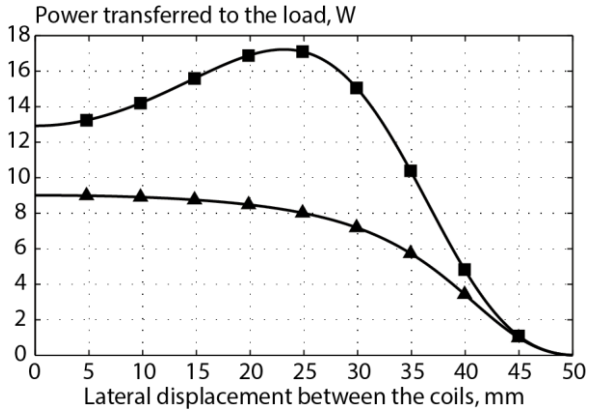

Figure 3: Load power as a function of lateral displacements for the case of a frequency tracking (▲) and for fixed operating frequency with critical coupling at ~25 mm (■) [20]

We proposed so called space-frequency approach to the design problem [20]. The main idea behind this method is that the geometric configuration of a coils couple, the LC-ciruits architecture and the frequency of the input signal chould be taken into account. Such a task can be accomplished using one key characteristics – coupling coefficient *k*. It is calculated as followes:

$$k = \frac{M}{\sqrt{L_R L_T}} \quad (1)$$

here M is mutual inductance, L_R, L_T are self-unductance of the receiving and transmitting coils respectevly.

It should be noted, that mutual inductance, self-inductance and, consequently, coupling coefficient can be derived from the purely geometric considerations [21]. At the same time, the value of the coupling coefficient determine two key characteristics. First is the point of a critical coupling, at which maximum load power (and 50% effectiveness) is acheived and which is calculated as follows:

$$k_{crit} = \frac{1}{\sqrt{Q_T Q_R}} \quad (2)$$

where Q_T and Q_R are the quality factors of the transmitter and receiver.

On the other hand, in the area of a strong coupling k can be used to define resonance requencies of a LC-circuits couple. If $k \gg k_{crit}$, it is possible to use following relatively simple formulas:

$$f_{odd} = \frac{f_{res}}{\sqrt{1+k}} \quad (3)$$

$$f_{even} = \frac{f_{res}}{\sqrt{1-k}} \quad (4)$$

where $f_{res} = 1/\left(2\pi\sqrt{LC}\right)$.

So, the key element of a design scheme is method for calculation of a mutual inductance between two arbitrary oriented coils. We have devoloped software for relatively fast calculation of a mutual inductance as a function of geometry using GPU computing [21]. When problem of a mutual inductance calculation is solved, next design procedure can be inplemented.

1°. Define design constraints. Usually it includes required load power P_L; acceptable range of changes in load power ΔP_L; maximum external radius of an implanted coil R_{Re}^{max}; range of axial, lateral, angular and rotational misalignments which must be tolerated, i.e. changes in the load power whithin this range of displacements must not exceeds ΔP_L.

2°. Define first raw design including source parameters as well as LC-circuit characteristics (C_R^0, C_T^0, L_R^0, L_T^0) and coils geometry (size and number of turns).

3°. Calculate set of a k values for a given range of the misalignments.

4°. Calculate set of a ΔP_L^1 values for a given range of the misalignments. If $\Delta P_L^1 > \Delta P_L$, start iterative procedure as follows:

4.1°. Raw tuning: increase the numbers of the turns. It will lead to fast increase the k values.

4.2°. Increase the external radius of the transmitting coil R_{Te}^{max}. It will lead to slow decrease of the k values.

Results of the implementation of the 4.1°. procedure are given in the fig. 4. It can be seen, that increase in the number of turns significantly increased stability.

Results of the implementation of the 4.2°. procedure are given in the fig. 5. It can be seen that increase in the transmitting coil external radius lead increased stability.

Proposed procedure can be classified as geometric procedure. It not include tuning of the circuit during the operation. Frequency tracking can help to improve the stability even further, and increasing the number of the turns in this case can be considered as a fine tuning because it chnges load power only slightly (fig.6, 7).

Discussion

As was pointed out in the second section of the presented paper, there are several types of misalignments and there is no universal solution to the problem of the IPU stability. It can be said, that for the large misalignments associated with the implant migration only possible solution is to use some means for detection of the implant position and correction of the transmitting coil position in order to achieve desired output characteristics. So, the positioning system must be included in the IPU.

Geometric optimization of the coils can effectively reduced effect of the misalignments of the order of R_{Te}^{max}. As it not involve sophistication of the IPU and IMD, it is desirable to use this method for compensation such misalignments.

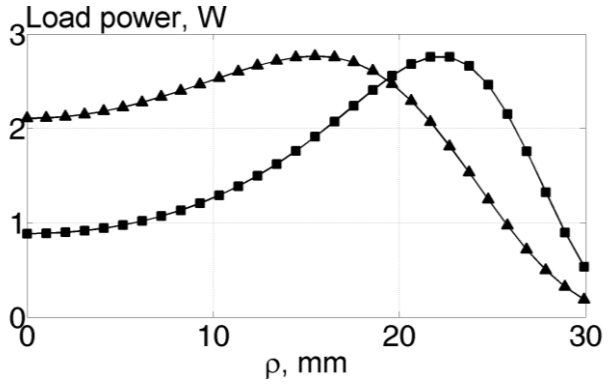

Figure 4: Load power as a function of lateral misalignments for coils with 13 (▲) and 7 (■) turns

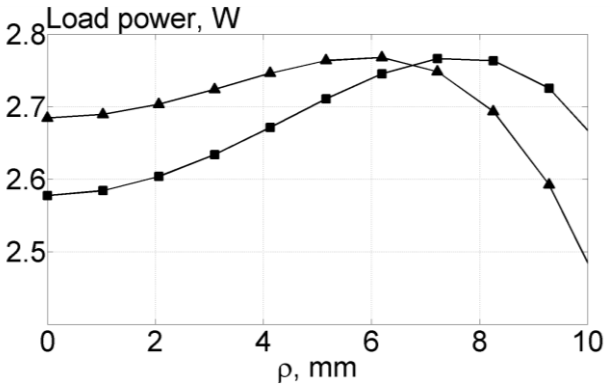

Figure 5: Load power as a function of lateral misalignments for coils with $R_{Te}^{max} = 12.5\ mm$ (▲) and $R_{Te}^{max} = 14.5\ mm$ (■)

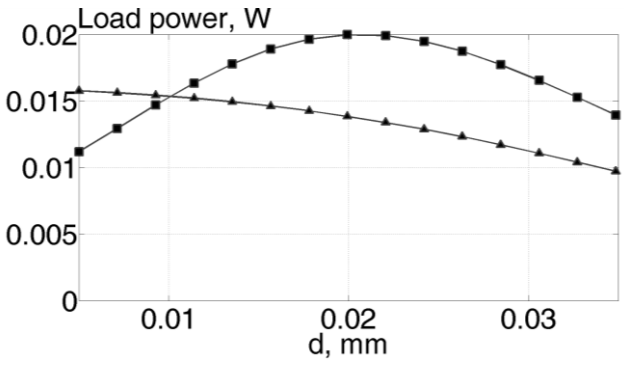

Figure 6: Load power as a function of axial distance between coils for fixed operating frequency (■) and frequency tracking (▲) for coils with 14 turns

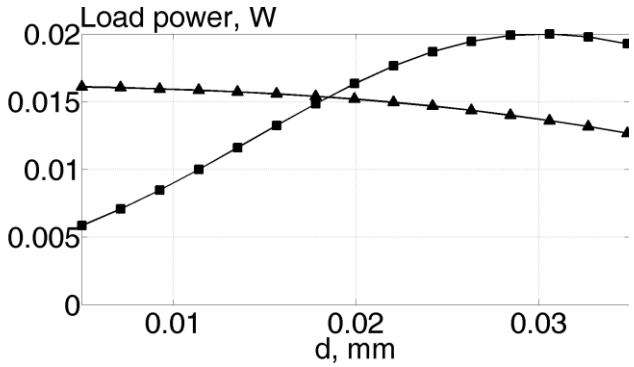

Figure 7: Load power as a function of axial distance between coils for fixed operating frequency (■) and freequency tracking (▲) for coils with 14 turns

The main restriction in the case of the geometric optimization is the medical considerations, which restricts implanted coil size. Thus, if the desirable level of stability cannot be achieved by geometric optimization, it is necessary to use frequency tracking, which provide additional stability at the cost of the decreased load power, device sophistication and reliability reduction.

Conclusions

In this paper, we have described design strategy for an IPU with the stable output characteristics. The core element of the strategy is the coil geometry optimization, which can be considered as the optimal way to deal with the misalignments of the order of R_{Te}^{max}. As this procedure can not assure a desirable level of stability in every case, it is necessary to combine the proposed method with others. In order to deal with implant migration it is necessary to use positioning system. In order to achieve very high stability it is possible to use frequency tracking.

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