TECHNICAL ASPECTS OF ELECTRICAL NEUROSTIMULATION.

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Abstract

This paper deals with technical aspects of electrical neurostimulation. Attention is given to problems of transmission of signals and power through inductive link created by coupled resonant circuits. Both geometric and electronic approaches are shown and compared. In geometric approach factors influencing mutual coupling are presented. In electronic approach two types of tuning of coupled resonant circuits are presented. The main stress is laid upon the principle of stagger tuning. At the end an example of stimulator using coupled resonant circuits stagger tuned is given.

Keywords:
neurostimulation, coupled resonant circuits, inductive coupling, mutual inductance, coefficient of coupling, misalignment analysis, geometric approach, electronic approach, coincidential tuning, stagger tuning.

1. Introduction

Successful neurostimulation of nerve and muscle tissue depends on solving technical problems connected with it. The most important problems are connected with delivery of power and signals into implanted stimulators.

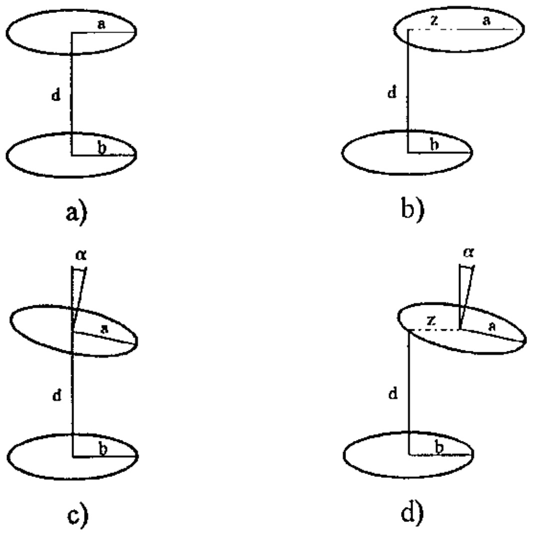
One of the possibilities for enabling transmission of information and power between external and implanted parts of neurostimulation system is the use of coupled resonant circuits (CRC). Transmission is allowed thanks to inductive coupling between external and implanted coils of primary and secondary resonant circuits (RC). Transmitter coil lies on the surface of skin and receiver coil is implanted inside the body. These coils are prevalingly planar, with or without ferrite core. Inductive links thus created, have several advantages comparing to their alternatives. For example, percutaneous link causes skin breach and so the health of pacient is endangered. Another possibility is to implant a battery. But some applications require so much power that frequent reimplantation or rechrarging is needed. Inductive link has non of these limitations, because it does not breach skin and delivers energy to stimulator from external source. These links, however, have their own difficulties. In the past there were problems connected with efficiency n, bandwidth B and sensitivity to misalignment. Thus the ways how to solve these problems were looked for. There exist two approaches to the design of inductive links created by CRC:

- Geometric approach
- Electronic approach

2. Geometric approach

In practical situations the transmitter and receiver coils are not placed coaxially, but they are misaligned. These misalignments are caused by activity of muscles and by wrong placement of transmitter coil. It is therefore necessary to speak of:

- Perfect alignment (Fig. 1a)



a) b) c) d)

Fig. 1
a) "Perfect Alignment"
b) "Lateral Misalignment"
c) "Angular Misalignment"
d) "General Case"

- Lateral misalignment (Fig. 1b)
- Angular misalignment (Fig. 1c)
- General case (Fig. 1d)

Assume planar single turn coils of circular shape (Fig. 1a). Mutual inductance is then specified as:

$$M=\frac{\mu_0}{4\pi}\oint_1\oint_2\frac{\overrightarrow{dl_1}.\overrightarrow{dl_2}}{r_{12}} \qquad (1)$$

where dl_1 is track element of the first coil and r_{12} is the magnitude of distance between elements $\overrightarrow{dl_1}$ and $\overrightarrow{dl_2}$.

This equation allows us to determine mutual inductance for whatever geometric arrangement of coils.

2.1 Factors influencing mutual inductance

During evaluation of mutual coupling it is necessary to think of these effects:

- Number of turns
- Shape of coils
- Mutual position

In spite of using mutual inductance it is more suitable to do analysis with coefficient of coupling k defined as follows:

$$k=\frac{M}{\sqrt{L_1.L_2}} \qquad (2)$$

For the couple of coils with number of turms n_1 and n_2, mutual inductance is multiplied by coefficient $n_1.n_2$, inductance of transmitter coil is $n_1^2.L_{1j}$ and inductance of receiver coil is $n_2^2.L_{2j}$, where L_{1j} and L_{2j} are inductances of single turn coils with the same shape as the coils considered. It is clear that the effect of number of turns is thus compensated during calculation of coefficient of coupling. If we know self inductances of coils with whatever number of turns, and mutual inductance M for the same system of coils but with one turn is multiplied by coefficient $n_1.n_2$, coefficient of coupling is counted according to (2).

2.2 Shape of coils

In computation of M and k one stands before another problem. Each of the disc coils has two diameters: internal and external. Which of them to use in evaluation of M and k? When solenoid coils are used there is a question concerning the distance between coils. A usual method for calculation of k and M which considers the shape of coils is based on definition of set of average parameters, such as average diameters, average distances, etc. This set is used for evaluation and the result is corrected by empirically got factors [5].

2.3 Mutual position

Change in mutual position causes change in mutual inductance between coils and thus influences the value of output voltage and current. Many applications require stable internal power supply and thus it is necessary to regulate output of receiver circuit [13]. If the change of output is too great, then much of the received power is not fed to stimulator but is waisted in regulator.

The main goal of geometric approach is to lower maximum value of coefficient of coupling k in order to lower its changes. This effect is reached by use of coils of different diameters. External coil has grater diameter than the implanted one [2], [7], [17]. While the smaller coil is inside the diameter of larger coil, magnetic flux lines shared by both coils are roughly the same and so the coefficient of coupling is approximately the same. But on the other side coils of unequal diameters share less magnetic flux lines than two equal coils and this causes decay of coefficient of coupling k. Lower coupling requires higher current in primary coil in order to get equal output from receiver coil. Greater current causes greater I^2R looses in primary coil and reduces efficiency. Moreover geometric approach is still sensitive to changes in coil separation; for a small separation (near field) their coupling drops proportionally with their separation. If the coil separation doubles, then their gain is cut in half [4]. This approach, therefore, only partially desensitizes the link gain with respect to the coil position.

3. Electronic approach

Efficiency of inductive link is always an important criterion because the freedom of person which has a neurostimulator implanted, is limited by the portability of transmitter power supply. If the inductive link is uneficient then implanted equipment of even modest conception requires too much power and thus influences the bulk of external part. As an example previous stimulators developed in Stanford University could be mentioned. These stimulators required a packet of batteries like a brick requiring recharging every 8 hours. In case that the system would be able to be in activity under supply of one or two 9V batteries, then the source would be small enough and does not interfere a person in his everyday activities.

Four basic combinations of CRC are used for transmission of signals and energy depending on the kind of exciting (voltage, current) and output signal (voltage, current). One speaks about following types of CRC:

- "Voltage in - Voltage out" (Fig. 2a)
- "Current in - Voltage out" (Fig. 2b)
- "Voltage in - Current out" (Fig. 2c)
- "Current in - Current out" (Fig. 2d)

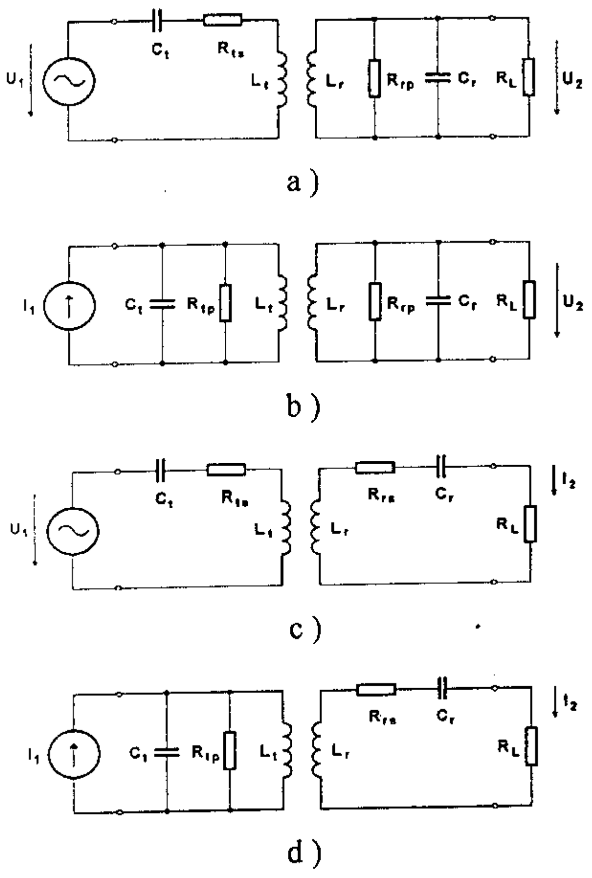


Fig.2
a) "Voltage in - Voltage out"
b) "Current in - Voltage out"
c) "Voltage in - Current in"
d) "Current in - Current out"
symbols:
L_t - inductance of transmitter coil
R_{ts} - serial resistance of transmitter coil
R_{tp} - parallel resistance of transmitter coil
C_t - capacitance of transmitter circuit
L_r - inductance of receiver coil
R_{rs} - serial resistance of receiver coil
R_{rp} - parallel resistance of transmitter coil
C_r - capacitance of receiver circuit
U_1 - input voltage
U_2 - output voltage
I_1 - input current
I_2 - output current

At present these types of tuning of CRC are used for neurostimulation aplications:

- Coincidential (synchronous) tuning
- Stagger tuning

3.1 Coincidential tuning of CRC

In this case resonant frequency of the transmitter circuit f_t is equal to the resonant frequency of receiver circuit f_r and both of them are equal to the carrier frequency of information f_o. Transmitter circuit is driven by oscillator with stable frequency . Information is obtained in receiver by demodulating amplitude modulated carrier frequency. This wave after filtration and rectification is used for power supply of stimulator. CRC are designed for operation near critical coupling. At critical coupling if $f_o = f_r = f_t$ then coupled resistance from

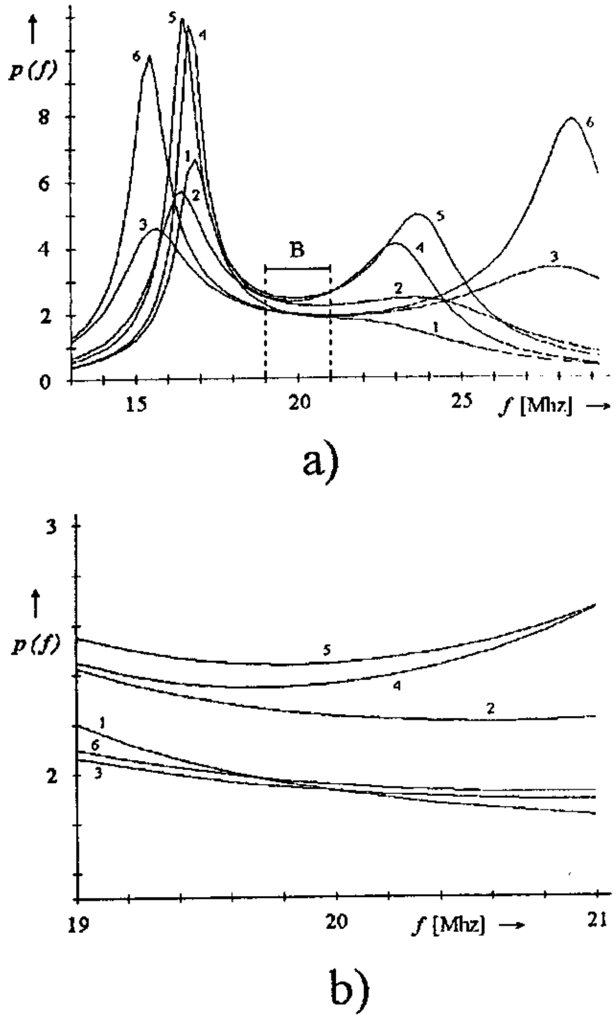


Fig.3
a) "Voltage Gain of Inductive Link Stagger-Tuned"
b) "Voltage Gain - Zoom"
symbols:
f_t - resonant frequency of transmitter RC
f_r - resonant frequency of receiver RC
f_o - frequency-modulated carrier
$f_t = 17.07$ MHz
$f_r = 22$ MHz
$f_o = 20$ MHz
L_t-L inductance of transmitter coil
L_r - inductance of receiver coil
$L_t = L_r = 1.96$ H
k - coefficient of coupling
R_L - load
B - bandwidth (19 MHz, 21 MHz)
1 .... $k = 0.2$ $R_L = 1k$
2 .... $k = 0.316$ $R_L = 1k$
3 .... $k = 0.5$ $R_L = 1k$
4 .... $k = 0.2$ $R_L = 3k$
5 .... $k = 0.257$ $R_L = 3k$
6 .... $k = 0.5$ $R_L = 3k$

secondary circuit to primary is equal to resistance of primary resonant circuit (RC). In this case the greatest amount of power is delivered from external RC to implanted RC (theorem of maximum power transfer) and efficiency of the link is 50%.

3.2 Stagger tuning of CRC

This principle of tuning of CRC is one of the modest trends in the field of electronic approach. Fig. 3a, and 3b, show the plots of voltage gain p versus frequency f for inductive link "Voltage in - Voltage out", which is designed for operation around 20MHz (19MHz - 21MHz). Parameters are: coefficient of coupling k and load R_L. The link is excited by a class D transmitter. Signal transmission is provided by frequency modulation (FM) of carrier frequency. The link is stagger tuned : resonant frequency of transmitter circuit f_t is lower and resonant frequency of receiver circuit f_r is higher than carrier frequency f_o. This causes so called " double - humps" in voltage gain plot. If the resonant frequences are chosen correctly poles of voltage gain are moving in the way as to compensate changes in voltage gain. If the coefficient of coupling is increased poles are moving away from f_o = 20MHz. Increased coupling would normally raise the gain at 20MHz, but the higher coupling has moved the poles away from 20MHz operating frequency, which would otherwise lower the gain. The net result, for this example, is that even though the coupling coefficient changes by 250 % (from 0.2 to 0.5), the gain changes less than 15 %. Since this approach is based on coupling, not geometry, it not only corrects for lateral and angular diplacement , as did the geometric approach, but it also handles coil separation, which the geometric solution did not. Notice that the gain changes smoothly around operating frequency (20MHz) giving a stable gain over a relatively large frequency band. Thus stagger tuning provides increase of the bandwidth without excessively loading the tuned circuits. Furthermore it allows to use equally sized coils for transmission and thus provides better values of efficiency comparing to links designed by geometric approach.

To take advantage of the efficiency afforded by the stagger tuned link's gain , the link needs a transmitter that can efficiently handle a variable load impedance while maintaining a constant driving voltage or current. Therefore it is necessary to use a class D transmitter, which meets these requirements and has a theoretical maximum efficiency 100%.

4. Design of CRC stagger tuned

The main goals of design of CRC stagger tuned are:

- to minimize the variation in output voltage, due to changing load and coupling, over a band of frequencies
- to keep a reasonably high input impedance, so a transmitter would not need to supply excessively large driving currents
- to make the input impedance inductive, so that a class D driver would switch cleanly
- to exceed a minimum of required gain
- to reach required efficiency

4.1 Circuit equations

Equations for computation of transmission, input & output impedances and efficiency are complicated and place consuming and so I do not publish them here. Complex analysis of all kinds of CRC is done in [1].

5. Conclusion

In this paper I presented an overlook on technical aspects of electrical neurostimulation. I described new method in energizing implanted neurotimulators - stagger tuning of CRC. This principle was successfully used for the design of inductive link of american stimulator *STIMULISS 8B* developed and constructed by researchers in Stanford University [4]. This is the " Voltage in - Voltage out" type of stimulator. Its curves of voltage gain coincide with those shown on Fig.3a, and Fig. 3b. Stagger tuning allows this stimulator to combine energetic and data link to one inductive link. The coils have ferrite cores in order to obtain high values of coefficient of coupling. The overall efficiency is *35%*, which allows the stimulator to be in activity for *16 hours a day* on two 9V batteries. The worst power consumption is about *140 mW* comparing to *500mW* of previous types of neurostimulators, which required a brick sized battery pack [4]. The principle of stagger tuning can be applied also to czechoslovak neurostimulators LSN 330 and LSN 340, which operate under coincidential tuning. Importance of CRC is still increasing due to use of artificial prostheses. But in general they can be used for signal and energy transmission through whatever barrage.

I believe that this paper will clarify problems concerning delivery of power and signals into implanted parts of electrical neurostimulator.

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