AN EFFICIENT, MISALIGNMENT-TOLERANT
0.6 W INDUCTIVE POWER TRANSMISSION LINK FOR IMPLANTABLE FES DEVICES

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SUMMARY

Inductive links are frequently used for powering of implanted devices for functional electrical stimulation (FES). They are used in applications where implanted batteries are not capable of supplying a sufficient amount of power over the time of implantation or where continuous data exchange with external components is necessary like in a leg pacemaker.

This paper describes an inductive power transmission link, which was developed for an implantable stimulator for direct stimulation of denervated muscles. The link transmits a power of 0.6 W over a distance range of 0 to 70 mm with an efficiency of more than 40%. The carrier frequency is around 2 MHz, the transmitter coil has a diameter of 80 mm, and the implant coil is 45 mm × 30 mm. Data transmission to the implant with amplitude shift keying (ASK) and back to the transmitter with passive telemetry can be added without major design changes.

The efficiency of the link was optimised with different approaches. A class E transmitter was used to minimise losses of the power stage. The geometry and material of the transmitter coil was optimised for maximum coupling. Phase lock techniques were used to achieve frequency tracking, keeping the transmitter optimally tuned at different coupling conditions caused by coil distance variations.

We chose the high range of coil spacing (0 to 70 mm) to care for lateral and angular misalignment, as it occurs in practical use. If the transmitter coil has a well defined and reliable position in respect to the implant, a smaller working range might be sufficient. Under these conditions the link can be operated in fixed frequency mode, and reaches even higher efficiencies of up to 68%.

STATE OF THE ART

The literature about inductive links offers many examples of inductive power links for implanted devices. There are links with high transferred power for short distances for implantable cardiac assist devices, like the total artificial heart. Miller /1/ described a 60 W link with an efficiency of 80% at a coil spacing of 5 mm. Links used to power implants for FES usually have lower transmitted power (<100 mW) and higher working range up to some centimeters. Clinical applications are, for example, cochlear prostheses and phrenic pacemakers /2/.

As we could see, there are many examples of inductive links both in research and in clinical practice. Nevertheless it was necessary for us to develop a new link for an implantable device for direct stimulation of the denervated posticus muscle /3/. In contrast to nerve stimulation this task is much more power consuming, it takes up to 30 mA of stimulation amplitude at 20 V. So the aim of this development was a maximum efficency at a high working range to keep the transmitter battery small and to achieve a safe operation of the system in everyday use.

MATERIAL AND METHODS

Coil design

The design of the transmitter coil affects the efficiency of the link in different ways: 1. Donaldson /4/ found that there exists an optimum transmitter coil diameter to obtain a maximum coupling coefficient for given coil spacing and geometry of the implanted coil. 2. The material of the coil can help to minimise resistive losses caused by the skin effect. 3. The coil forms an integrated part of the transmitter stage and has to meet design criteria from that side. Following the methods of Donaldson we found a coil diameter of 80 mm to be the optimum for a coil to coil distance of 35 mm. To make coupling insensitive to axial rotation we chose a circular coil. As a material we used Litz wire with 420 individually isolated strands of 50 µm diameter copper wire. We limited the number of turns to 10 to keep the transmitter smaller and more lightweight, for better convenience for the users.

Transmitter design

Use of class E transmitters has become common in the design of inductive links. The DC to AC efficiency of these amplifiers theoretically reaches 100% (/5/, /6/). A principle circuit is included in Fig.1.

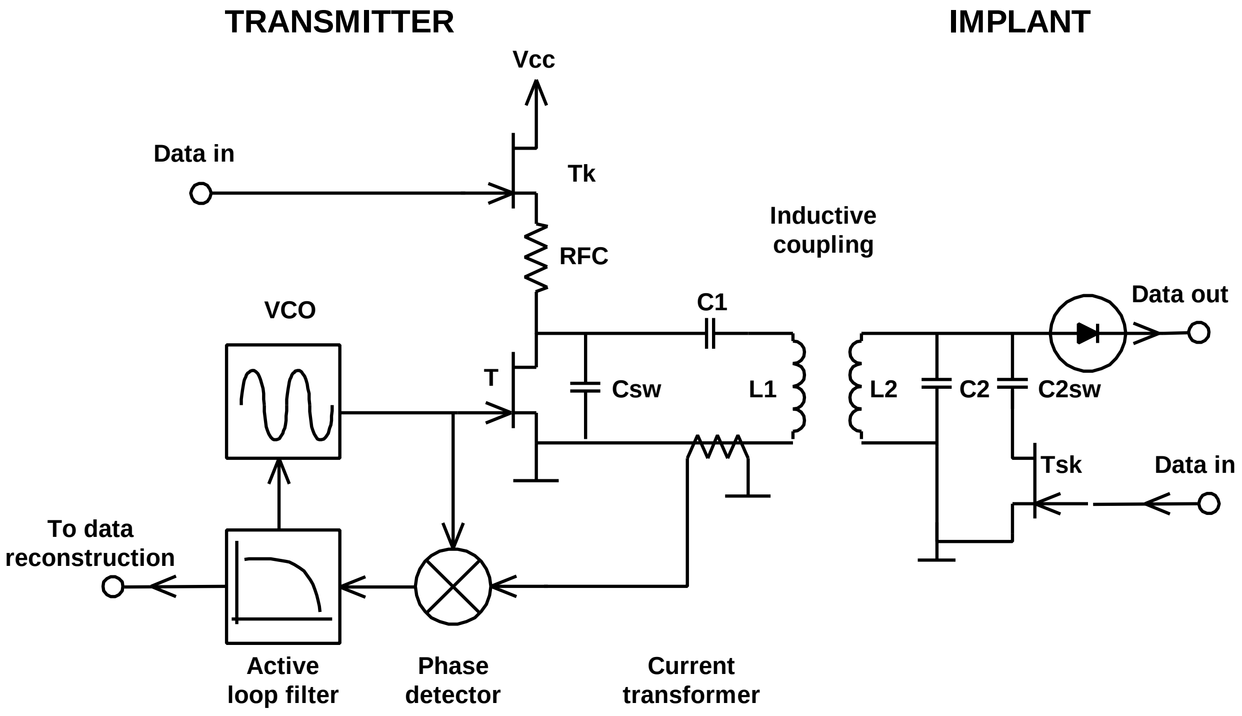

Fig.1: Principle circuit of the transmitter and the implant

Thorough analysis of the complete transmitter in MathCad© and Pspice© with the given transmitter and implant coils led to the calculated component values for C1 and Csw. A phase locked loop (PLL) circuit adjusts the transmitter frequency to different coupling conditions automatically. The transmitter current phase is sensed over a transformer, and compared to the output of the VCO. The resulting phase signal, adequately low-pass filtered, then controls the frequency of the VCO to form a self-adjusting transmitter.

To transmit data to the implant we used an MOS transistor (Tk) to key the transmitter supply on and off. The radio frequency choke (RFC) together with the capacitor Csw and the input capacity of the switching transistor T forms a low pass filter. This effect limits the maximum data rate. The link was designed for bidirectional transmission with 9600 bits/s.

Load shift keying (LSK) by switching a capacitor (C2sw) in parallel to the secondary resonant circuit (L2, C2) over a MOS transistor (Tsk) was used for passive back-telemetry from the implant. Switching Tsk causes a phase shift in the transmitter. The phase detector output can then also be used to recover the data signal.

RESULTS

The transmitter we built as described above transmits a power of 0.6 W over a distance range from 0 to 70 mm with an efficiency of more than 40%. If the transmitter coil has a well defined and reliable position in respect to the implant, a smaller working range might be sufficient. Under these conditions the link can be operated in fixed frequency mode, and reaches even higher efficiencies of up to 68%. Figure 2 gives an impression of the overall DC-to-DC performance.

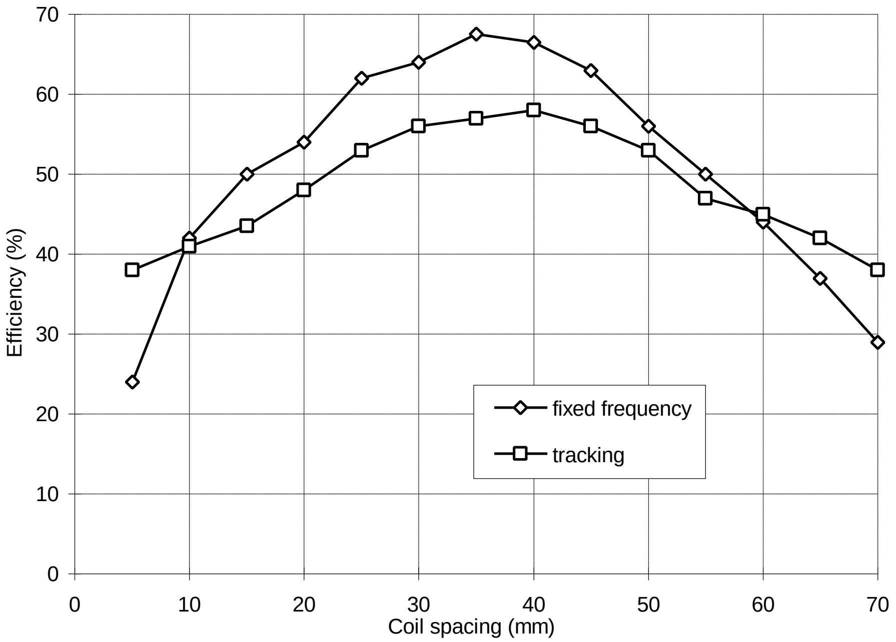

Fig.2: Efficiency of the link over coil-to-coil distance for the frequency-tracking and the fixed-frequency transmitter

DISCUSSION

With the design principles described above we achieved satisfactory energy transmission with a high amount of transmitted energy and a wide area of coil spacings compared to other links for FES devices. However our implant still contains a linear power regulator. This causes significant losses if the transmitter power is not lowered at smaller coil spacings. We overcame this by using a fixed-current power supply for the transmitter stage. Further improvement can be added by use of the telemetered implant supply voltage for online control of the transmitter power.

REFERENCES

/1/ J. A. Miller, G. Bélanger, T. Mussivand, "Development of an Autotouned Transcutaneous Energy Transfer System,“ *ASAIO Journal*, vol. 39, pp. M706-M710, July-Sept. 1993

/2/ H. Thoma, H. Gerner, J. Holle, P. Kluger, W. Mayr, B. Meister, G. Schwanda, H. Stöhr, "The Phrenic Pacemaker - Substitution of Paralysed Functions in Tetraplegia," *ASAIO*, vol. 10, no. 3, pp. 472-479, July-Sept. 1987

/3/ B. Luger, W. Mayr, S. Sauermann, M. Zrunek, "Diaphragm EMG as a Control Signal for FES of the Denervated Posticus Muscle," in *Proc. of the 4th International Muscle Symposium*, Zürich, pp. 136-139, March 1995

/4/ N. de N. Donaldson, T. A. Perkins, "Analysis of Resonant Coupled Coils in the Design of Radio Frequency Transcutaneous Links,“ *Med. & Biol. Eng. & Computing,* no. 21, pp. 612-627, Sept. 1983

/5/ N. O. Sokal, A. D. Sokal, "Class E - A New Class of High-Efficiency Tuned Single-Ended Switching Power Amplifiers,“ *IEEE J. Solid-State Circuits*, vol. SC-10, pp. 168-176, June 1975

/6/ M. K. Kazimierczuk, "Class E Tuned Power Amplifier with Nonsinusoidal Output Voltage,“ *IEEE J. Solid-State Circuits*, vol. SC-21, pp. 575-581, Aug. 1986

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