Load Optimization of an Inductive Power Link for Remote Powering of Biomedical Implants

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Abstract— **This article presents the analysis of the power efficiency of the inductive links used for remote powering of the biomedical implants by considering the effect of the load resistance on the efficiency. The optimum load condition for the inductive links is calculated from the analysis and the coils are optimized accordingly. A remote powering link topology with a matching network between the inductive link and the rectifier has been proposed to operate the inductive link near its optimum load condition to improve overall efficiency. Simulation and measurement results are presented and compared for different configurations. It is shown that, the overall efficiency of the remote powering link can be increased from 9.84% to 20.85% for 6 mW and from 13.16% to 18.85% for 10 mW power delivered to the regulator, respectively.**

I. Introduction

Inductive links are the most commonly used method for remote powering of implantable devices [1]–[4]. This method does not require any transcutaneous wires, which may cause infections, or any implantable batteries, which need to be replaced at the end of their lifetime.

The inductive link presented in this article will be used for remote powering of a cortical implant, which will monitor the neural activity in the brain. The implant will be remotely powered from a close–by external reader, which is operated from a battery. This battery should be small and light weight, and should be able to last for a long time for patient mobility and comfort. Therefore, the efficiency of the remote powering link should be as high as possible. Furthermore, the efficiency is also critical in terms of safety issues, in order to keep the EM fields absorbed by the tissues as small as possible.

A typical remote powering link for implantable devices is composed of four main parts: (1) power amplifier, (2) inductive link, (3) rectifier, and (4) voltage regulator. In order to obtain high overall efficiency, each block should be designed and operated properly. The power efficiency of the remote powering link is generally limited by the inductive link as the coupling between the inductors is usually very small. Therefore, attention must be paid in the design of the inductive links to obtain high power efficiency.

Previous studies have shown that the power efficiency of the inductive link can be increased by proper design of the geometry of the coils [3], [4]. However, the efficiency of the inductive link is also a function of the load impedance, which is the input impedance of the next stage in the power link (usually the rectifier). In order to increase the overall efficiency, the effect of the load impedance on the power efficiency of the inductive link should be analyzed.

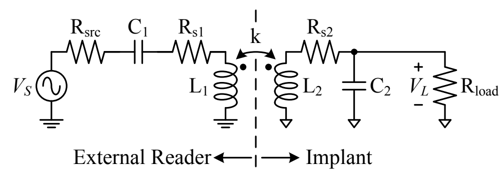

Fig. 1. Simplified model of a typical inductive link used for remote powering of the implantable devices [4].

This study presents the analysis of the power efficiency of the inductive links with respect to its load impedance. The coils are designed by using the optimization procedure proposed in [4], for different load conditions. A modified remote powering link architecture is proposed with the addition of a matching network between the inductive link and the rectifier, in order to operate the inductive link near its optimum load condition. The simulation and measurements results are presented to verify the improvement of the power efficiency with the addition of the matching network.

II. Optimization for Optimum Load Condition

Fig. 1 shows the simplified model of a typical inductive link used for remote powering of the implantable devices [4]. By following the analysis for calculating the power transfer function, as given in [4], and without making the narrowband approximation, it can be found that an optimum load condition exists which maximizes the power efficiency from the source to the load at the resonance frequency. This optimum load can be calculated as:

$$R_{load,opt} = \frac{Q_2 R_{s2}\sqrt{\left(Q_2^2+1\right)\left(R_{s1}+R_{src}\right)+k^2 Q_1 Q_2 R_{s1}}}{\sqrt{R_{s1}+R_{src}+k^2 Q_1 Q_2 R_{s1}}} \qquad (1)$$

where, Q_1 and Q_2 are the quality factors of the coils.

Knowing that there is an optimum load condition for the power efficiency, the coils are designed by following a modified version of the optimization procedure introduced in [4]. During the optimization procedure, first, a fixed resistive load ($R_{L,ch}$) has been chosen to find the best coil geometry for that chosen load. Then, the same procedure is applied by choosing another $R_{L,ch}$ value until the maximum efficiency is found. Table I shows the fixed system parameters used in this optimization procedure.

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TABLE I

Fixed System Parameters for the Inductive Link

Parameter	Value	Explanation
f_0	1 MHz	Operation frequency
R_{src}	3 Ω	Source (amplifier) resistance
h	35 μm	Conductor thickness
s_{min}	100 μm	Minimum conductor spacing
w_{min}	100 μm	Minimum conductor width
$od_{i,max}$	10 mm	Max. outer dimension of implanted coil
d	5 mm	Distance between the coils

The designed coils are fabricated on printed circuit boards (PCB). The characterization of these coils have shown that the resistances of the inductors are larger than expected values and the effective thickness of the copper is calculated to be 25 μm for the fabricated coils. Therefore, the simulations are modified in order to model the increase in the resistances of the inductors. All of the coils presented in this study are optimized for 35 μm copper thickness, but simulated with 25 μm.

Fig. 2 shows the power efficiency vs. the load resistance of the inductive link for different $R_{L,ch}$ values chosen during the optimization procedure (including losses on R_{src}). By using the component values obtained from these designs, the optimum load resistance given in (1) can be approximated as:

$$R_{load,opt} \simeq \frac{Q_2^2 R_{s2}}{\sqrt{1+k^2 Q_1 Q_2}} \tag{2}$$

The denominator of (2) lies between 1.75 and 2.27 for these designs, and for simplicity, it has been approximated as 2, in this study. Therefore, the optimum load can be written as:

$$R_{load,opt} \simeq \frac{Q_2^2 R_{s2}}{2} \simeq \frac{R_{p2}}{2} \tag{3}$$

where, R_{p2} is the parallel equivalent of the parasitic resistance of implanted coil. By using the approximate maximum efficiency given in [4] and inserting (3) to this equation, the power efficiency for optimum load can be approximated as:

$$\eta_{opt} \simeq \frac{2/3}{1+\frac{3}{k^2 Q_1' Q_2}} \tag{4}$$

where, $Q_1' = \omega L_1/(R_{s1}+R_{src})$. The validity of these equations should be checked for other coil designs.

Fig. 3 shows the extracted results from the optimization procedure (including losses on R_{src}). It can be seen that the optimum load resistance is around 2.75 Ω, which is found for $R_{L,ch} = 3$ Ω design, resulting in 35.84% power efficiency. However, the secondary inductance value is very small for this design, and hence, may cause a shift in the resonance frequency due to parasitic inductances from the interconnects in the setup. Therefore, 20 Ω design has been chosen to keep the inductive link more immune to parasitics, at the cost of a slight decrease in the efficiency. The optimum load resistance and corresponding power efficiency for 20 Ω design are found to be 16.37 Ω and 32.08% (with losses on R_{src}), respectively. It can also be seen from Fig. 3 that the approximations given in (3) and (4) are applicable around the optimum load condition.

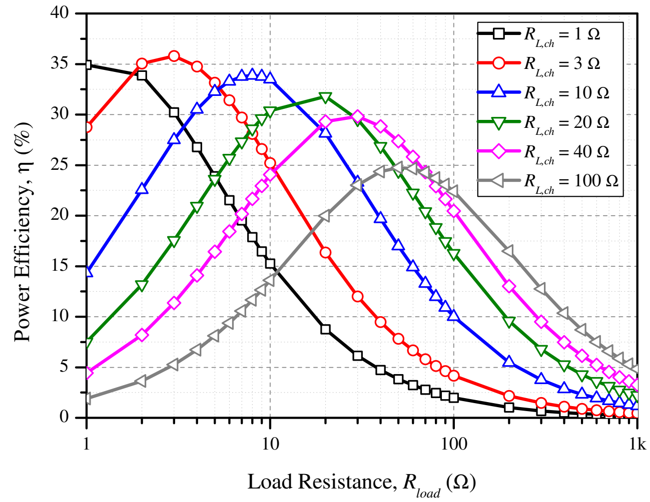
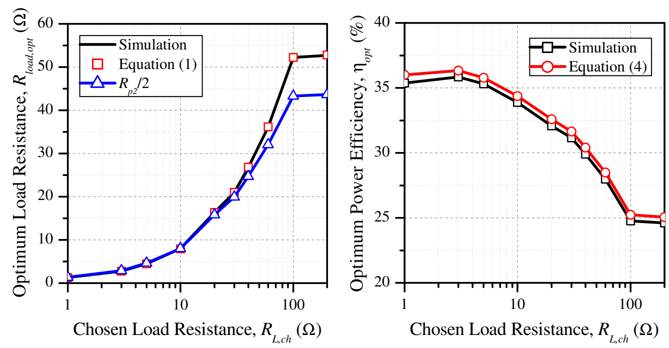


Fig. 2. Power efficiency vs. load resistance for different $R_{L,ch}$ values (including losses on R_{src}).



(a) (b)

Fig. 3. Extracted results from the optimization (a) $R_{load,opt}$ vs. $R_{L,ch}$ and (b) η_{opt} vs. $R_{L,ch}$ (including losses on R_{src}).

III. Matching to Optimum Load

Fig. 4 shows the proposed remote powering link for the implantable devices with the added matching network. The rectifier topology given in this figure is composed of two envelope detectors, which operate in the alternating phases of the input signal. The voltage regulator is connected to the output of the rectifier to produce a clean supply voltage to the implanted electronics. For proper operation of the regulator presented in [5], the output of the rectifier should always be larger than 2.1 V. Moreover, the ripple should be less than 100 mV_{pp} to have sufficiently clean dc voltage at the output of the regulator. For this study, the average rectifier output voltage is chosen as 2.2 V, with added tolerance.

The diodes used in the rectifier are NXP BAT54S Schottky barrier diodes and the rectifier capacitances (C_{r1} and C_{r2}) are chosen to be 47 nF. From the simulations, the input impedance of the designed rectifier is found to be $87.25 - j10.35$ Ω for 10 mW power delivered to the regulator.

As the optimum load resistance of the inductive link and real part of the simulated rectifier input impedance are quite

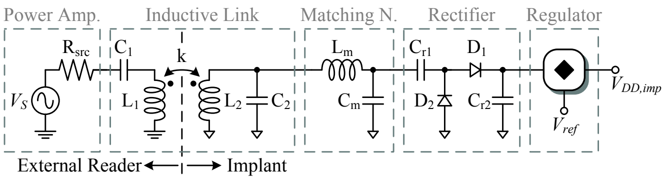


Fig. 4. Proposed remote powering link for implantable devices.

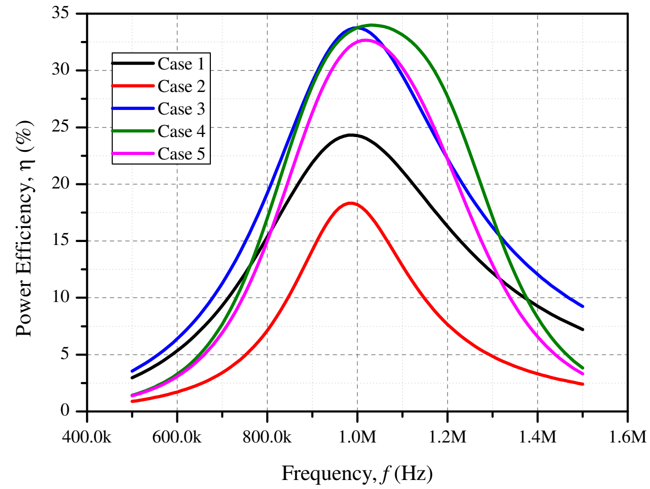


Fig. 5. Simulation results of the power transfer function of the inductive link for different cases. Case 1: 100 Ω design, directly connected to rectifier input impedance model ($87.25 - j10.35$ Ω). Case 2: 20 Ω design, directly connected to rectifier input impedance model. Case 3: 20 Ω design, 20 Ω resistive load. Case 4: 20 Ω design, ideal matching network tuned to 20 Ω at f_0. Case 5: 20 Ω design, practical matching network tuned approximately to 20 Ω at f_0 (off–the–shelf components with 1.8 Ω series resistance at L_m).

different, direct connection of the rectifier to the output of the inductive link will reduce the power efficiency of the inductive link. In order to operate the inductive link near its optimum load condition, a simple matching network can be used between the inductive link and the rectifier, as shown in Fig. 4. If the losses on L_m can be kept low and if the load matching can be properly maintained, the overall efficiency of the power link will be increased. In this study, the matching network is designed to match the rectifier input impedance to 20 Ω, while the rectifier is delivering 10 mW to the regulator.

Fig. 5 shows the comparison of the power transfer function of the inductive link for several different cases. Comparing Case 1 (the maximum efficiency obtained without using matching network) with Case 5 (the efficiency obtained with the practical matching network), it can be seen that the inductive link efficiency is increased from 24.28% to 32.52% by using the matching network to operate the inductive link near its optimum load condition. Similarly, the efficiency of the inductive link for Case 1 and Case 5 are found to be 6.29% and 16.48%, respectively, for 1 mW power delivered to the regulator. These simulation results show that the power efficiency of the inductive link can be easily improved with introducing a matching network between the inductive link and the rectifier. Moreover, the efficiency can be further enhanced by using a higher Q inductor in the matching network.

IV. Characterization Results

Unless mentioned, the losses of the power amplifier and the regulator in Fig. 4 are not included in the results presented.

The fabricated coils are characterized by changing the load resistance of the inductive link. Fig. 6(a) shows the simulated and measured efficiency of the inductive link vs. load resistance. As seen from the figure, the measured response of the inductive link is close to the expected response.

Secondly, the performance of the rectifier with the matching network and without the inductive link is measured, by sweeping the power delivered from the rectifier to a resistive load, while keeping the average voltage at the output of the rectifier at 2.2 V. Fig. 6(b) shows the simulated and measured efficiencies of the matching network and the rectifier. Addition of the matching network decreases the efficiency of the rectifier due to the losses on the matching network components. As will be shown later, these losses are compensated with the help of loading the inductive link near its optimum load.

After that, the inductive link has been connected to another matching network and rectifier pair, in order to characterize the inductive link performance with a complex non-linear load. For these measurements, the average rectifier output voltage is again kept at 2.2 V and the output power delivered from the rectifier to the load is swept. Fig. 6(c) shows the simulated and extracted efficiencies for the inductive link while connected to the matching network and the rectifier. Extracted efficiency is obtained by calculating the input impedance of the matching network from previous measurements and simulating the inductive link performance with the complex input impedance of the matching network.

Fig. 6(d) shows the simulated efficiencies of the overall power link (inductive link & matching network & rectifier) without the matching network (MN), with lossless MN, and with lossy MN. It can be seen that the efficiency of the overall link increases around 10%, by using the matching network.

Fig. 7 shows the overall efficiency of the remote powering link vs. load power delivered to the regulator. For 10 mW delivered power, the measured efficiency of the overall power link is found to be 18.85%. It can be seen from the figure that, the measured and simulated overall power efficiencies are close to each other. The differences between the simulations and measurements result from the cumulated effects coming from the discrepancies in the circuit component values of the inductive link, matching network, and the rectifier.

Comparing Fig. 7 with Fig. 6(d), for 10 mW power delivered from the rectifier to the regulator, the efficiency of the overall link has been increased from 13.16% to 18.85% by using a matching network. Similarly, it increases from 5.91% to 18.96% for 3 mW and from 9.84% to 20.85% for 6 mW cases, respectively. Moreover, by using a higher Q inductor at the matching network, the efficiency can be further improved up to 26% ($Q = \infty$, see Fig. 6(d)). Additionally, the performance can also be enhanced with a higher efficiency

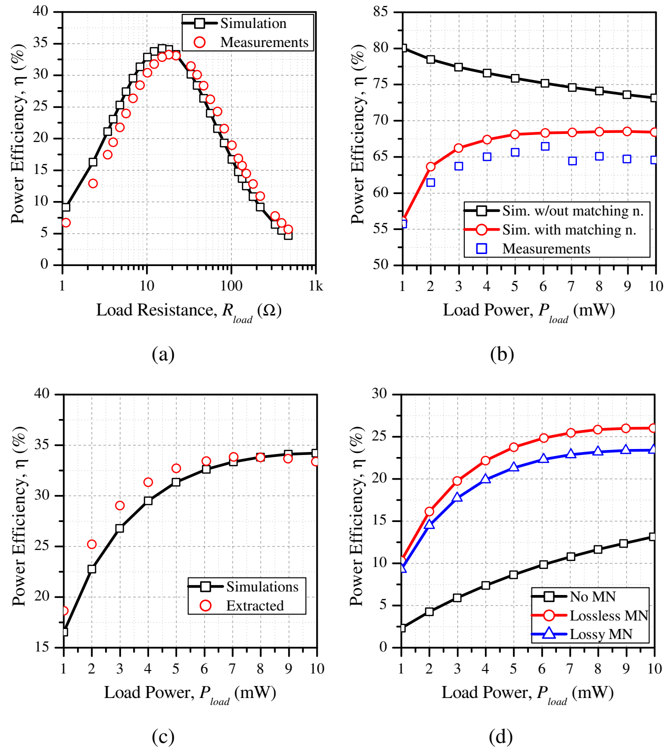


Fig. 6. (a) Simulated and measured inductive link efficiency vs. load resistance. (b) Simulated and measured efficiencies of the rectifier with the matching network. (c) Simulated and extracted efficiencies for the inductive link vs. power delivered from the rectifier. (d) Simulated efficiencies of the overall link without the matching network (MN), with a lossless MN, and with a lossy MN.

rectifier. The comparison of the measurement and simulation results clearly indicate that using a matching network between the inductive link and the rectifier increases the efficiency of the remote powering link by operating the inductive link near its optimum load condition. For all of the cases, the maximum ripple voltage is measured to be less than 80 mV_{pp}, which satisfies the requirements of the voltage regulator.

V. Conclusions

In this article, optimum load condition of the inductive links used for remote powering of the biomedical implants is investigated. For a typical inductive link, an optimum load condition has been found. Around this optimum load condition, the optimum load value can be approximated to the half of the parallel equivalent of the parasitic resistance of the implanted coil, which allows a simple intuition for the optimum load of a designed inductive link.

For the cortical implant system, the optimum load and the corresponding inductive link efficiency (with losses on R_{src}) are found to be 2.75 Ω and 35.84%, respectively. However, 20 Ω design, which has 32.08% maximum efficiency, is chosen to make the link more immune to parasitics from the setup.

A remote powering link with a matching network has been proposed, in order to match the optimum load condition of the inductive link with the input impedance of the rectifier.

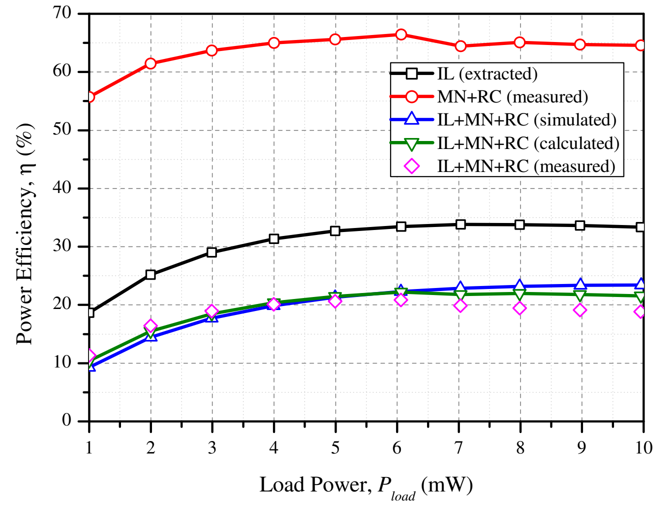


Fig. 7. Simulated and measured overall link performance for the remote powering link (IL: inductive link, MN: matching network, RC: rectifier). Calculated overall efficiency (green) is found by multiplying the extracted inductive link efficiency (black) with measured rectifier efficiency (red).

This matching network helps relaxing the design of both the inductive link and the rectifier.

The simulations and measurements of the inductive link, matching network, and the rectifier are presented and the power efficiencies for different cases are compared. From these results, it is found that by using a proper matching network with off–the–shelf components, the efficiency of the inductive link can be increased from 24.28% to 32.52% at the resonance frequency. Moreover, with this method, the efficiency of the overall remote powering link can be increased from 5.91% to 18.96% for 3 mW, from 9.84% to 20.85% for 6 mW, and from 13.16% to 18.85% for 10 mW power delivered to the regulator, respectively.

The overall efficiency of the system can be further increased by using a higher Q inductor at the matching network and/or by designing a higher efficiency rectifier.

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