Optimal Design of Energy Efficient Inductive Links for Powering Implanted Devices

Fabian L. Cabrera, and F. Rangel de Sousa

Radio Frequency Laboratory - EEL/CTC
Federal University of Santa Catarina, Florianópolis, Brazil

January, 2014

Implanted devices benefits:

- Chronic diseases treatment
- Health monitoring
- Brain-machine interfaces

Main goal: Noninvasive implants

Motivation

Implanted devices benefits:

- Chronic diseases treatment
- Health monitoring
- Brain-machine interfaces

Main goal: Noninvasive implants

Challenges:

- Miniaturization
- Autonomy

Batteries limit both!

Motivation

Implanted devices benefits:

- Chronic diseases treatment
- Health monitoring
- Brain-machine interfaces

Main goal: Noninvasive implants

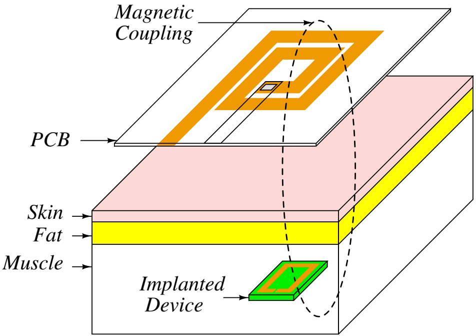
Challenges:

- Miniaturization
- Autonomy

Batteries limit both!

One solution:
Inductive Link Powering

Inductive Link



- Maximum power is restricted due to tissue heating
- Link efficiency must be optimized

- How to design inductive links for optimal power transferring efficiency?

- How to design inductive links for optimal power transferring efficiency?
- Low frequencies are commonly used (<20MHz)
- Low frequencies require big inductors, that are not desired.
- Recently arose the possibility of powering the implants in GHz frequencies, according to the electrical properties of tissues [1].

[1] A. Poon, S. O'Driscoll, and T. Meng, "Optimal Frequency for Wireless Power Transmission into Dispersive Tissue", May 2010.

- How to design inductive links for optimal power transferring efficiency?

- Low frequencies are commonly used (<20MHz)

- Low frequencies require big inductors, that are not desired.

- Recently arose the possibility of powering the implants in GHz frequencies, according to the electrical properties of tissues [1].

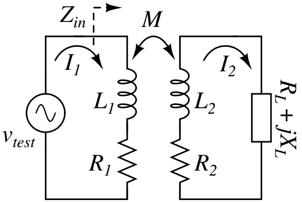
- We propose a method for optimal design of the inductive links considering all the associated constraints.

[1] A. Poon, S. O'Driscoll, and T. Meng, "Optimal Frequency for Wireless Power Transmission into Dispersive Tissue", May 2010.

Outline

- Electrical Model
- Formulation of the Problem
- Results
- Conclusions

- Electrical Model
- Formulation of the Problem
- Results
- Conclusions



$$\eta = \frac{\textit{Power at the load}}{\textit{Power delivered to the link}} = \frac{|I_2|^2 R_L}{|I_1|^2 \Re e\{Z_{in}\}}$$

when $X_L = -\omega L_2$:

$$\frac{1}{\eta} = \frac{R_1 R_2}{(\omega M)^2}\left(\frac{R_2}{R_L} + 2 + \frac{R_L}{R_2}\right) + \frac{R_2}{R_L} + 1$$

$$\frac{1}{\eta} = \frac{R_1 R_2}{(\omega M)^2}\left(\frac{R_2}{R_L} + 2 + \frac{R_L}{R_2}\right) + \frac{R_2}{R_L} + 1$$

$M = k\sqrt{L_1 L_2}$ $\quad Q_1 = \omega L_1 / R_1$ $\quad Q_2 = \omega L_2 / R_2$ $\quad p = R_2 / R_L$

Function to be optimized

$$\frac{1}{\eta} = \frac{1}{k^2} \cdot \frac{1}{Q_1} \cdot \frac{1}{Q_2} \cdot \underbrace{(p + 2 + \frac{1}{p}) + p + 1}$$

Electrical Model

$$\frac{1}{\eta} = \frac{R_1 R_2}{(\omega M)^2}\left(\frac{R_2}{R_L} + 2 + \frac{R_L}{R_2}\right) + \frac{R_2}{R_L} + 1$$

$$M = k\sqrt{L_1 L_2} \qquad Q_1 = \omega L_1 / R_1 \qquad Q_2 = \omega L_2 / R_2 \qquad p = R_2 / R_L$$

Function to be optimized

$$\frac{1}{\eta} = \frac{1}{k^2} \cdot \frac{1}{Q_1} \cdot \frac{1}{Q_2} \cdot \underbrace{(p + 2 + \frac{1}{p}) + p + 1}$$

- Coupling factor squared

$$\frac{1}{\eta} = \frac{R_1 R_2}{(\omega M)^2}\left(\frac{R_2}{R_L} + 2 + \frac{R_L}{R_2}\right) + \frac{R_2}{R_L} + 1$$

$M = k\sqrt{L_1 L_2}$ $\quad Q_1 = \omega L_1/R_1$ $\quad Q_2 = \omega L_2/R_2$ $\quad p = R_2/R_L$

Function to be optimized

$$\frac{1}{\eta} = \frac{1}{k^2} \cdot \frac{1}{Q_1} \cdot \frac{1}{Q_2} \cdot \underbrace{(p + 2 + \frac{1}{p}) + p + 1}$$

- Coupling factor squared
- First Inductor quality factor

$$\frac{1}{\eta} = \frac{R_1 R_2}{(\omega M)^2}\left(\frac{R_2}{R_L} + 2 + \frac{R_L}{R_2}\right) + \frac{R_2}{R_L} + 1$$

$$M = k\sqrt{L_1 L_2} \qquad Q_1 = \omega L_1 / R_1 \qquad Q_2 = \omega L_2 / R_2 \qquad p = R_2 / R_L$$

Function to be optimized

$$\frac{1}{\eta} = \frac{1}{k^2} \cdot \frac{1}{Q_1} \cdot \frac{1}{Q_2} \cdot \underbrace{(p + 2 + \frac{1}{p}) + p + 1}$$

- Coupling factor squared
- First Inductor quality factor
- Second Inductor quality factor

Electrical Model

$$\frac{1}{\eta} = \frac{R_1 R_2}{(\omega M)^2} \left(\frac{R_2}{R_L} + 2 + \frac{R_L}{R_2} \right) + \frac{R_2}{R_L} + 1$$

$M = k\sqrt{L_1 L_2}$ $\quad Q_1 = \omega L_1 / R_1$ $\quad Q_2 = \omega L_2 / R_2$ $\quad p = R_2 / R_L$

Function to be optimized

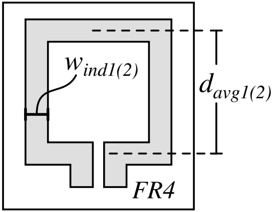
$$\frac{1}{\eta} = \frac{1}{k^2} \cdot \frac{1}{Q_1} \cdot \frac{1}{Q_2} \cdot \underbrace{(p + 2 + \frac{1}{p}) + p + 1}$$

- Coupling factor squared
- First Inductor quality factor
- Second Inductor quality factor
- Load matching dependence

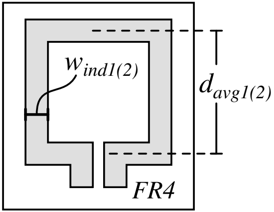
Outline

- Electrical Model
- Formulation of the Problem
- Results
- Conclusions

Problem Formulation



Given:	The implanted inductor size	d_{avg1}, w_{ind1}
	The distance between the inductors	d
Find:	The external inductor size	d_{avg1}, w_{ind1}
	The load proportion	p
	The frequency	f
In order to:	maximize efficiency	η



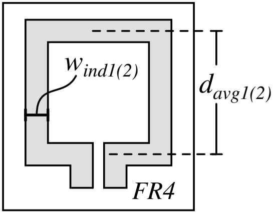
Written as a Geometric Program:

$$\begin{cases} \textit{minimize}: & \frac{1}{k^2}\cdot\frac{1}{Q_1}\cdot\frac{1}{Q_2}\cdot(p+2+\frac{1}{p})+p+1 \\ \textit{subject to}: & (A)\ F_{min}.w_{ind1} \leq d_{avg1} \\ & (B)\ w_{min} \leq w_{ind1} \\ & (C)\ d_{avg1}+w_{ind1} \leq d_{max} \end{cases}$$

Reciprocal of the efficiency

Define the design space boundary

Optimization Problem

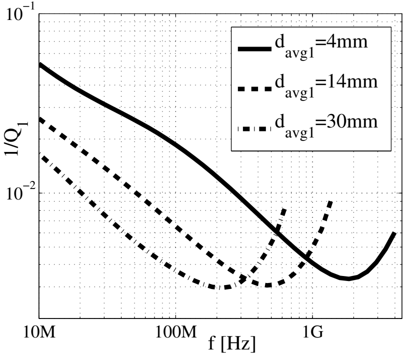


Given data for this example:

- $d_{avg2} = 4\ mm$
- $w_{ind2} = 0.5\ mm$
- d was swept between 1 mm and 35 mm
- Material surrounding the link: air

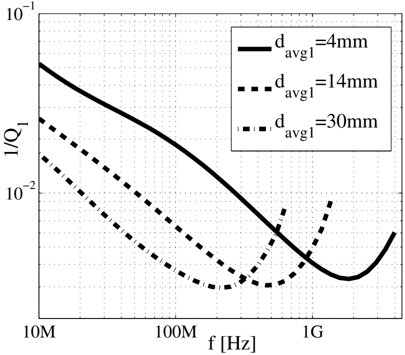
Models

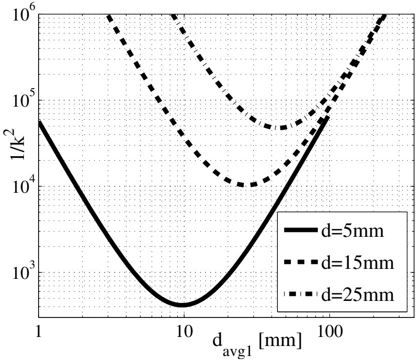
- $1/Q_1 = f_1(d_{avg1}, w_{ind1}, f)$
- $1/Q_2 = f_2(f)$



Models

- $1/Q_1 = f_1(d_{avg1}, w_{ind1}, f)$
- $1/Q_2 = f_2(f)$
- $1/k^2 = f_3(d_{avg1})$

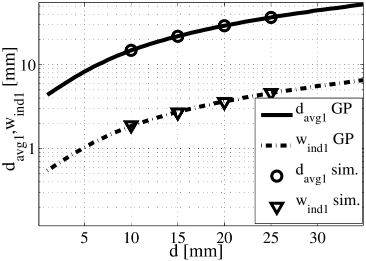




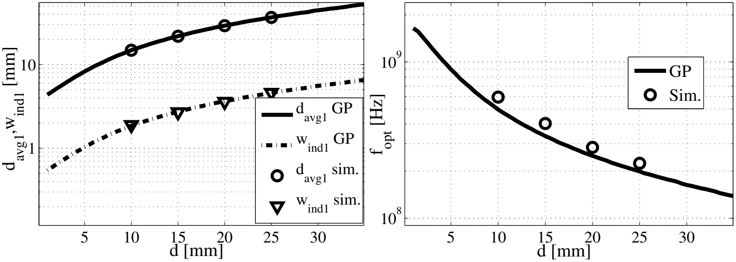
Outline

- Electrical Model
- Formulation of the Problem
- Results
- Conclusions

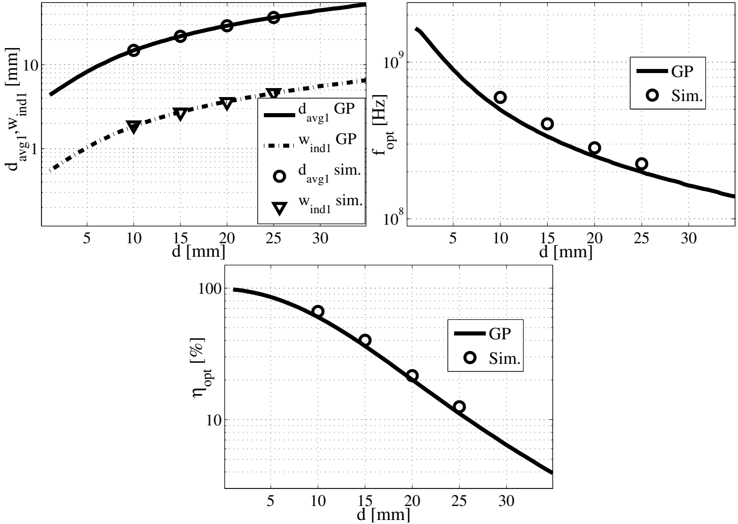
Geometric Program Results



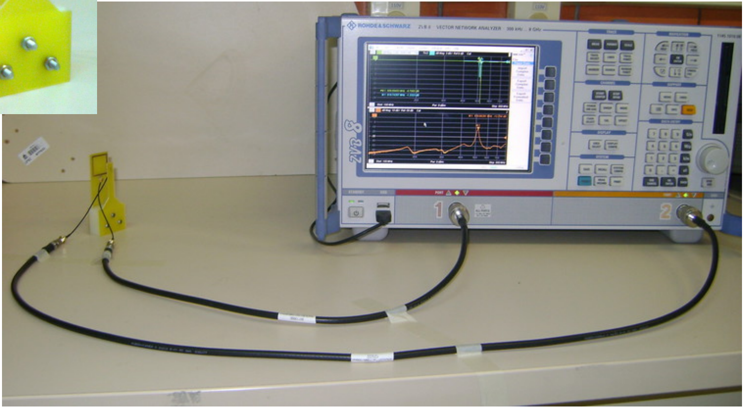
Geometric Program Results

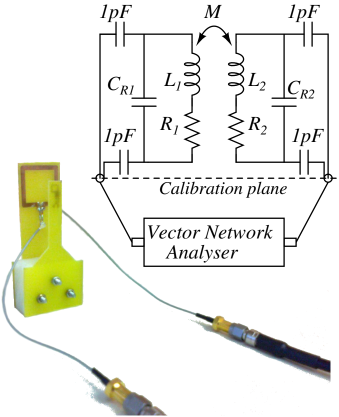


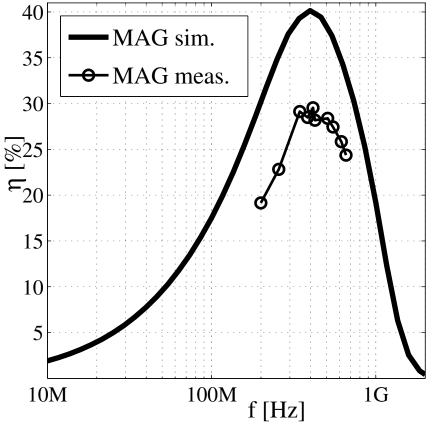
Geometric Program Results



Implementation and Test for d=15mm







d_{avg1}	22 mm	d_{avg2}	4 mm	d	15 mm
w_{ind1}	2.7 mm	w_{ind2}	0.5 mm		
f_{opt}(Sim.)	398 MHz	f_{opt}(Meas.)	415 MHz	Δf_{opt}	17 MHz
η_{opt}(Sim.)	40%	η_{opt}(Meas.)	30%	$\Delta\eta_{opt}$	-10%

- Electrical Model
- Formulation of the Problem
- Results
- Conclusions

Conclusions

- We presented a method for optimal design of inductive links, considering both the frequency and the geometry of the link.
- As an example, when the implanted inductor has a diameter of 4 mm and the distance between the inductors is 15 mm, the diameter of the designed external inductor is 22 mm and the maximum efficiency measured is 30% at 415 MHz.
- For the dimensions used as example, the optimal frequency is between 120 MHz and 1.5GHz. Which is higher than the frequency commonly used, but lower than the estimated frequency when only the tissues are considered.

Questions?