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Powering Implantable Devices from a Surface

With Application to Physiological Monitoring in Mice

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A thesis submitted in partial fulfilment of the requirements for the degree of

Doctor of Philosophy in Bioengineering

The University of Auckland, New Zealand

2011

Abstract

Magnetic fields offer the prospect of transferring energy through the skin to power active implantable devices for indefinite periods of time. Inductive power transfer is an attractive technology for smart implantable devices to overcome limitations of batteries and avoid the infection risk associated with direct electrical connections. This thesis presents work addressing the problem of powering implantable devices for monitoring the physiological status of laboratory mice.

Although the fundamental principles for transferring power inductively are very well understood, there are many practical issues to be resolved when transferring power over a variable air gap. A typical mouse is only 20 grams in body weight, and a key aspect to miniaturising a telemetry system is the elimination of an internal battery. This necessitates an inductive power link capable of continuously supplying power as the mouse moves freely within the confines of its home cage. An inductive power link involves a primary inductive coil outside the animal, and a secondary coil located inside the animal. To accommodate the mouse application, the link must operate when the secondary has an arbitrary orientation and location with respect to the primary. To solve this problem, a planar winding structure is proposed that is placed under the cage of the animal. Advantages of a planar structure over cage encompassing primary coil structures include proximity to the animal, more uniform magnetic coupling and scalability to cover different size cages.

Development of this system resulted in an analytical method of determining which one of arbitrary number of independently located primary coils can transfer power to an arbitrarily oriented pickup with the greatest efficiency. A consequence of the analysis was the development of a method of optimising the primary and pickup structures in isolation from each other. This method was developed for the arbitrary coupling problem but is applicable to any loosely coupled inductive link – including those which utilise a ferromagnetic pickup core.

The thesis concludes with the implementation and evaluation of a prototype inductive link for powering an arbitrarily oriented implant. Results from the prototype are compared to predictions based on the analyses developed. The agreement of results validates the proposed methods and confirms that a planar winding structure is capable of continuously powering an arbitrarily oriented implant.

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NOMENCLATURE AND SYMBOLS

Acronyms

2D - Two Dimensions
3D - Three Dimensions
AC - Alternating Current
ADC - Analogue to Digital Converter
AWG - American Wire Gauge
BP - Blood Pressure
BPM - Beats Per Minute
DC - Direct Current
DUT - Device Under Test
EMI - Electromagnetic Interference
ESR - Equivalent Series Resistance
HF - High Frequency
ICPT - Inductively Coupled Power Transfer
ISM - Industrial Scientific and Medical (Band)
LC - Inductor-Capacitor connection
LR - Inductor-Resistor connection
MOSFET - Metal Oxide Semiconductor Field Effect Transistor
OD - Outside Diameter
PCB - Printed Circuit Board
PWM - Pulse Width Modulation
QFN - Quad Flat No leads
RF - Radio Frequency
RMS - Root Mean Square
SEM - Standard Error of the Mean
SNA - Sympathetic Nerve Activity
SOC - System On Chip
SPI - Serial Peripheral Interface
TET - Transcutaneous Energy Transfer

Symbols

Fundamental Quantities

$\vec{\boldsymbol{a}}_{\boldsymbol{x}}, \vec{\boldsymbol{a}}_{\boldsymbol{y}}, \vec{\boldsymbol{a}}_{\boldsymbol{z}}$ - Cartesian Unit Vector
B - Magnetic Field Magnitude (Tesla)
$\boldsymbol{B}$ - Magnetic Field Vector (Tesla)
C - Capacitor (Farads)
δ - Skin Depth (m)
E - Energy (Joules)
f - Frequency (Hz)
$G(s/j\omega)$ - Transfer Function

i - Instantaneous Current / Envelope of Current (Amperes)
I - Current Magnitude (Amperes)
j - Complex Operator ($\sqrt{-1}$)
k - Magnetic Coupling Coefficient
L - Self-Inductance (Henrys)
λ - Flux Linkages (Volt Second/Weber Turns)
M - Mutual Inductance (Henrys)
μ - Permeability (H/m)
$\mu_{\mathbf{0}}$ - Vacuum Permeability (H/m)
$\mu_{\mathbf{r}}$ - Relative Permeability (Unit-less)
$\mathbf{n}$ - Unit Normal Vector
$\boldsymbol{\Phi}$ - Magnetic Flux (Weber)
ω - Angular Frequency (Radians/s)
Q - Quality Factor
r - Radius (m)
R - Resistance (Ω)
ρ - Resistivity ($\mathrm{S{\cdot}m^{-1}}$)
t - Time (seconds)
T - Period (seconds)
τ - Time Constant (seconds)
θ - Phase Angle
v - Instantaneous Voltage (Volts)
V - Voltage Magnitude (Volts RMS)
V_{FW} - Diode Forward Voltage (Volts)
W - Power (Watts)

Primary Symbols

a,b - Outside Dimensions of Rectangular Coil (m)
B_0 - Normalized Magnetic Field Strength ($B/(N_1I_1)$)
$B_{0\text{-}min}$ - Global or Local Minimum Field Strength ($B/(N_1I_1)$)
C_1 - Primary Tuning Capacitance (Farads)
d_i - Spiral Coil Inner Diameter (m)
d_o - Spiral Coil Outer Diameter (m)
E_{L1} - Primary Winding Energy (Joules)
I_1 - Primary Current (A_{RMS})
L_{10} - Single Turn Equivalent Primary Self-inductance (Henrys)
L_1 - Primary Self-inductance (Henrys)
l_c - Conductor Length (m)
N_1 - Primary Turns
W_h - Window Height (m)
ω_{crit} - Frequency Where 10% of R is Due to Eddy Current (rads/s)
R_1 - Primary Winding Resistance (Ω)

R_{10} - Single Turn Equivalent Primary Winding Resistance (Ω)
s - Space between Adjacent Tracks (m)
t_c - Sheet Conductor Thickness (m)
w - Track Width (m)
X_1 - Primary Winding Potential (Vs^2/Am^4)

Secondary (Pickup) Symbols

A_c - Pickup Area (m^2)
A_e - Effective Pickup Area (m^2)
η_2 - Secondary Efficiency
β - $N_2/N_{2\ PMAX}$
C_2 - Secondary Tuning Capacitance (Farads)
E_{L2} - Secondary Winding Energy (Joules)
F - Fill Factor (Unit-less)
I_2 - Secondary Current (A_{RMS})
I_{sc} - Short Circuit Current (A_{RMS})
L_2 - Secondary Self-inductance (Henrys)
L_{20} - Single Turn Equivalent Secondary Self-inductance (Henrys)
N_2 - Secondary Turns
N_f - Fluxmetric Demagnetizing Factor
N_m - Magnetometric Demagnetizing Factor
Q_2 - Secondary Quality factor
R_2 - Secondary Winding Resistance (Ω)
R_{20} - Single Turn Equivalent Secondary Winding Resistance (Ω)
R_L - Load Resistance (Ω)
R_{L0} - Single Turn Equivalent Secondary Load (Ω)
Γ - Ratio of Length upon Diameter
V_{OC} - Open Circuit Voltage (V_{RMS})
W_h - Window Height (m)
W_r - Window Radius (m)
X_2 - Secondary Winding Potential (Am^4/ V)
μ_{core} - Effective Core Permeability $\equiv A_e/A_c$ (unit-less)

Link Properties

A - Link Gain (Unit-less)
η - Efficiency (Unit-less)
E_M - Mutual Energy (Joules)
k - Coupling Coefficient (Unit-less)

M - Mutual inductance (Henrys)
M_0 - Single Turn Equivalent Mutual inductance (Henrys)
P_{IN} - Input Power (Watts)
P_{OUT} - Output Power (Watts)
ω_0 - Resonant Frequency (Radians)
X - Link Potential (Unit-less)

Subscripts

1 - Primary Component
2 - Secondary Component
10 - Single Turn Equivalent Primary Component
20 - Single Turn Equivalent Secondary Component
AC - AC value
$const$ - Constant Quantity
DC - DC value
ΔV - Quantity Evaluated over a Partial Volume
eq - Equivalent
E - Eddy Component (of Resistance)
MAX - Maximum value or value at which maximum is obtained
MIN - Minimum value
OC - Open circuit
P - Peak
$Pk\text{-}Pk$ - Peak to Peak
PAR - Parallel Equivalent
REF - Reference
RMS - Root Mean Square
SER - Series Equivalent
SC - Short circuit
x,y,z - Cartesian Component of Quantity