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Bert Lenaerts · Robert Puers

# Omnidirectional Inductive Powering for Biomedical Implants

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# Abstract

In the biomedical world, inductive links are long since valued for their ability to transmit electric power transcutaneously. They are employed for wireless powering of implants when the limited energy budget of batteries just is inadequate. Also data communication can be established in both directions over an inductive link. Especially the combination of power and data transmission makes an inductive link very attractive for certain applications. It enables the fabrication of highly integrated and cheap transponders, as are encountered in typical radio frequency identification (RFID) applications for instance.

This book starts its discourse with the fundamental physics of magnetic induction. As a next step, the design equations for an inductive power link are worked out. The appropriate variables are introduced to gain a clear insight into the impact of design choices on the link performance. Methods are provided for optimising an inductive link with respect to power transmission, efficiency or coupling sensitivity. A separate chapter is devoted to the power electronics required for effectively transmitting and receiving power, being an inverter, a rectifier and possibly a voltage regulator. All suitable topologies are considered. Issues regarding design and practical realisation are treated as well.

Novel applications pose new challenges. Inductive powering of a capsule endoscope is a good illustration thereof. The random orientation and position of such a capsule within the abdominal volume demands for novel concepts regarding magnetic coupling. Two possible approaches towards omnidirectional coupling are presented, one encompassing multiple external coils, the other integrating multiple coils at the receiving side. Both concepts are investigated on a general, theoretical basis and techniques are presented by which their worst-case performance can be assessed. For inductive powering of a capsule endoscope, three orthogonal receiving coils turn out to yield the best result in terms of transmitted power and efficiency.

The developed theory is put into practise through the actual realisation of an inductive link for a capsule endoscope. The experimental findings obtained with the realised test model confirm the theoretical predictions. The transmission of at least 150 mW of usable power is demonstrated for all possible positions and orientations of the capsule within the abdominal volume.

Issues regarding the interaction with biological tissue are addressed. The existing literature on biological effects of electromagnetic fields is summarised in a separate chapter. The compliance with the exposure regulations of the inductive link for the capsule endoscope is checked. A conductive shield is applied to the transmitting coil to prohibit any capacitive interaction with the patient's body. This brings the whole-body dissipation down below the prescribed levels and eliminates the possibility of the patient detuning the resonant coil driver by movement of his trunk or arms.

Changes in self-inductance of the transmitting coil, provoked by mechanical deformation for instance, are not supported in a resonant inverter topology. Advanced

coil drivers incorporating dedicated control systems are required for driving flexible or deformable coils. The final chapter of this book presents a closed-loop class E inverter topology that compensates automatically for changes in transmitting coil inductance by means of a transductor, which is an inductor with an electrically controllable inductance value. The principal advantage of transductor compensation over earlier reported techniques, is that the operation frequency remains fixed. The realised laboratory test model copes with inductance variations up to 27% without the class E efficiency ( $> 80\%$ ) or the magnetomotive force (125 to 138 ampere-turns) being notably affected.

# List of Abbreviations

AC	Alternating Current
AM	Amplitude Modulation
BJT	Bipolar Junction Transistor
CCVS	Current Controlled Voltage Source
CMOS	Complementary Metal-Oxide-Semiconductor
DC	Direct Current
ECG	Electrocardiogram
ELF	Extremely Low Frequency
EM	Electromagnetic
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
emf	Electromotive Force
ESR	Equivalent Series Resistance
FDTD	Finite-Difference Time-Domain
FE	Finite Element
FM	Frequency Modulation
IARC	International Agency for Research on Cancer
IC	Integrated Circuit
ICNIRP	International Commission on Non-Ionising Radiation Protection
ISM	Industrial-Scientific-Medical
LDO	Low Dropout
mmf	Magnetomotive Force
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
MRI	Magnetic Resonance Imaging
NMR	Nuclear Magnetic Resonance
NP0	Negative-Positive-Zero
PC	Phase Comparator
PCB	Printed Circuit Board
RF	Radio Frequency
RFID	Radio Frequency Identification
RMS	Root-Mean-Square
SAR	Specific Absorption Rate
SMD	Surface Mount Device
TF	Transfer Function
TTL	Transistor-Transistor Logic
VNA	Vector Network Analyser
WCM	Worst-Coupling Map
ZVS	Zero-Voltage-Switching

# List of Symbols

$\alpha$	load factor, $= \omega C_2 R_L$
$\delta$	skin depth, penetration depth
$\tan \delta$	loss tangent, $= \frac{1}{Q}$
$\epsilon$	electric permittivity
$\epsilon_0$	$8.854 \cdot 10^{12}$ F/m, electric permittivity of free space
$\epsilon_r$	relative electric permittivity
$\zeta$	normalised time derivative of the switch voltage at switch opening
$\eta$	link efficiency
$\eta_{DC/AC}$	inverter efficiency
$\eta_{rect}$	rectifier efficiency
$\theta$	spherical coordinate (Fig. 5.9)
$\lambda$	wavelength
$\mu$	magnetic permeability
$\mu_0$	$4\pi \cdot 10^{-7}$ H/m, magnetic permeability of free space
$\mu_r$	relative magnetic permeability
$\rho$	free charge density
$\sigma$	electric conductivity
$\phi$	magnetic flux
$\varphi$	spherical and cylindrical coordinate
$\psi$	phase difference
$\omega$	angular frequency ( $= 2\pi f$ )
$\omega_0$	angular (self-)resonance frequency of an LC tank
$\mathbf{A}$	magnetic vector potential, divergence free
$\tilde{\mathbf{A}}$	magnetic vector potential including the gradient field $-\frac{j}{\omega} \nabla V$
$A_\varphi$	out-of-plane magnetic potential in an axisymmetric geometry, amplitude (phasor) or DC value
$A_z$	out-of-plane magnetic potential in a 2-D wire geometry, amplitude (phasor) or DC value
$\mathbf{B}$	magnetic flux density
$\mathbf{B}_1$	primary magnetic flux density
$C$	capacitance
$C_L$	inter-winding capacitance
$\mathbf{D}$	electric flux density
$D$	duty cycle
$d$	distance
$\mathbf{E}$	electric field
$E$	electric field amplitude (phasor) or DC value
$E_\varphi$	out-of-plane electric field in an axisymmetric geometry, amplitude (phasor) or DC value
$\mathbf{E}_c$	conservative electric field component



<b>E<sub>m</sub></b>	magnetically induced, non-conservative electric field component
<i>e</i>	2.718...
<i>f</i>	frequency
<i>f<sub>0</sub></i>	(self-)resonance frequency of an LC tank
<b>H</b>	magnetic field
<b>I</b>	current vector of a multi-port network containing all current phasors
<i>I</i>	current amplitude (phasor) or DC value
<i>i</i>	current in time domain
<b>J</b>	conduction current density
<b>J<sup>e</sup></b>	external source current density
<i>J<sub>φ</sub></i>	out-of-plane electric current density in an axisymmetric geometry, amplitude (phasor) or DC value
<i>J<sub>φ</sub><sup>e</sup></i>	out-of-plane external source current density in an axisymmetric geometry, amplitude (phasor) or DC value
<i>J<sub>z</sub><sup>e</sup></i>	out-of-plane external source current density in a 2-D model, amplitude (phasor) or DC value
<i>k</i>	coupling coefficient, $= \frac{M}{\sqrt{L_1 L_2}}$
<i>L</i>	self-inductance
<i>L<sub>0</sub></i>	one-turn equivalent self-inductance, $= \frac{L}{N^2}$
<i>L<sub>s</sub></i>	parasitic series inductance of a switch
<i>L'</i>	effective self-inductance of an LRC network
<i>l</i>	length
<i>M</i>	mutual inductance
<i>M<sub>0</sub></i>	one-turn equivalent mutual inductance, $= \frac{M}{N_1 N_2}$
<i>N</i>	number of turns of a winding
<b>n̂</b>	unity vector perpendicular to a boundary
<i>n</i>	square root of the inductance ratio of two coupled coils, $= \sqrt{\frac{L_2}{L_1}}$
<b>P</b>	orientation vector of a sole secondary coil
<i>P</i>	power
<i>p<sub>R<sub>ON</sub></sub></i>	normalised conduction losses due to <i>R<sub>ON</sub></i>
<i>p<sub>t<sub>f</sub></sub></i>	normalised turn-off losses due to finite fall time <i>t<sub>f</sub></i>
<i>p<sub>L<sub>s</sub></sub></i>	normalised switching losses due to series inductance <i>L<sub>s</sub></i>
<i>Q</i>	quality factor
<i>R</i>	resistance
<i>R<sub>0</sub></i>	one-turn equivalent resistance, $= \frac{R}{N^2}$
<i>R'</i>	effective series resistance of an LRC network
<i>R<sub>eq</sub></i>	equivalent resistance seen at the primary side of an inductive link due to the coupled secondary circuit
<i>R<sub>CC</sub></i>	equivalent DC resistance seen at the input of an inverter
<i>R<sub>DC</sub></i>	equivalent load resistance connected to the output of a rectifier
<i>R<sub>L</sub></i>	equivalent secondary load resistance
<i>R<sub>sys</sub></i>	equivalent load resistance posed by the remote electronic system
<i>r</i>	cylindrical coordinate
<i>S</i>	area

$s$	Laplace variable (complex)
$t$	time
$t_f$	fall time
$\mathbf{V}$	voltage vector of a multi-port network containing all voltage phasors
$V$	electric potential or voltage, amplitude (phasor) or DC value
$V_{CC}$	DC input voltage of an inverter
$V_{DD}$	DC supply voltage to an electronic system
$V_{DC}$	DC output voltage of a rectifier
$V_{FW}$	voltage drop over a diode in conduction
$V_{loop}$	loop voltage over an axisymmetric structure, amplitude (phasor) or DC value
$v$	voltage in time domain
$X$	link potential, $= \frac{\omega^2 M^2}{R_1 R_2}$
$x$	Cartesian coordinate
$y$	Cartesian coordinate
$\mathbf{Z}$	impedance matrix of a multi-port network (complex)
$Z$	impedance (complex)
$Z_{eq}$	equivalent impedance seen at the primary side of an inductive link due to the coupled secondary circuit
$z$	Cartesian coordinate

# Contents

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