Omnidirectional Inductive Powering for Biomedical Implants

ANALOG CIRCUITS AND SIGNAL PROCESSING SERIES

Consulting Editor: **Mohammed Ismail.** ***Ohio State University***

Titles in Series:

THE GM/ID DESIGN METHODOLOGY FOR CMOS ANALOG LOW POWER INTEGRATED CIRCUITS
Jespers, Paul
ISBN: 978-0-387-47100-6
ULTRA LOW-POWER BIOMEDICAL SIGNAL PROCESSING
AN ANALOG WAVELET FILTER APPROACH FOR PACEMAKERS
Haddad, Sandro A.P., Serdijn, Wouter A.
ISBN: 978-1-4020-9072-1
OMNIDIRECTIONAL INDUCTIVE POWERING FOR BIOMEDICAL IMPLANTS
Lenaerts, Bert, Puers, Robert
ISBN: 978-1-4020-9074-5
BIOPOTENTIAL READOUT CIRCUITS FOR PORTABLE ACQUISITION SYSTEMS
Yazicioglu, Refet Firat, Van Hoof, Chris, Puers, Robert
ISBN: 978-1-4020-9092-9
STRUCTURED ANALOG CMOS DESIGN
Stefanovic, Danica, Kayal, Maher
ISBN: 978-1-4020-8572-7
LOW POWER UWB CMOS RADAR SENSORS
Paulino, Nuno, Goes, João, Steiger Garção, Adolfo
ISBN: 978-1-4020-8409-6
ANALYSIS AND DESIGN OF QUADRATURE OSCILLATORS
Oliveira, L.B., Fernandes, J.R., Filanovsky, I.M., Verhoeven, C.J.M., Silva, M.M.
ISBN: 978-1-4020-8515-4
THE GM/ID DESIGN METHODOLOGY FOR CMOS ANALOG LOW POWER INTEGRATED CIRCUITS
Jespers, Paul G.A.
ISBN-10: 0-387-47100-6
LOW-POWER HIGH-SPEED ADCS FOR NANOMETER CMOS INTEGRATION
Cao, Zhiheng, Yan, Shouli
ISBN: 978-1-4020-8449-2
SUBSTRATE NOISE COUPLING IN RFICS
Helmy, Ahmed, Ismail, Mohammed
ISBN: 978-1-4020-8165-1
CIRCUIT AND INTERCONNECT DESIGN FOR HIGH BIT-RATE APPLICATIONS
Veenstra, Hugo, Long, John R.
ISBN: 978-1-4020-6882-9
HIGH-RESOLUTION IF-TO-BASEBAND SIGMADELTA ADC FOR CAR RADIOS
Silva, Paulo G.R., Huijsing, Johan H.
ISBN: 978-1-4020-8163-7
MULTI-BAND RF FRONT-ENDS WITH ADAPTIVE IMAGE REJECTION
A DECT/BLUETOOTH CASE STUDY
Vidojkovic, V., van der Tang, J., Leeuwenburgh, A., van Roermund, A.H.M.
ISBN: 978-1-4020-6533-0
SILICON-BASED RF FRONT-ENDS FOR ULTRA WIDEBAND RADIOS
Safarian, Aminghasem, Heydari, Payam
ISBN: 978-1-4020-6721-1
DESIGN OF HIGH VOLTAGE XDSL LINE DRIVERS IN STANDARD CMOS
Serneels, Bert, Steyaert, Michiel
ISBN: 978-1-4020-6789-1
HIGH-LEVEL MODELING AND SYNTHESIS OF ANALOG INTEGRATED SYSTEMS
Martens, Ewout S.J., Gielen, Georges
ISBN: 978-1-4020-6801-0
BASEBAND ANALOG CIRCUITS FOR SOFTWARE DEFINED RADIO
Giannini, Vito, Craninckx, Jan, Baschirotto, Andrea
ISBN: 978-1-4020-6537-8
CMOS MULTI-CHANNEL SINGLE-CHIP RECEIVERS FOR MULTI-GIGABIT OPT...
Muller, P., Leblebici, Y.
ISBN 978-1-4020-5911-7
ANALOG-BASEBAND ARCHITECTURES AND CIRCUITS
FOR MULTISTANDARD AND LOW-VOLTAGE WIRELESS TRANSCEIVERS
Mak, Pui In, U, Seng-Pan, Martins, Rui Paulo
ISBN: 978-1-4020-6432-6
FULL-CHIP NANOMETER ROUTING TECHNIQUES
Ho, Tsung-Yi, Chang, Yao-Wen, Chen, Sao-Jie
ISBN: 978-1-4020-6194-3

For other titles published in this series, go to
www.springer.com/series/7381

Bert Lenaerts · Robert Puers

Omnidirectional Inductive Powering for Biomedical Implants

Springer

Dr. Bert Lenaerts
Dr. Robert Puers

Katholieke Universiteit Leuven
Dept. Electrical Engineering
(ESAT)
Kasteelpark Arenberg 10
3001 Leuven
Belgium
Robert.Puers@esat.kuleuven.be

ISBN 978-1-4020-9074-5 ISBN 978-1-4020-9075-2 (eBook)
DOI 10.1007/978-1-4020-9075-2

Library of Congress Control Number: 2008934392

Printed on acid-free paper

9 8 7 6 5 4 3 2 1

springer.com

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

B. Lenaerts, R. Puers, *Omnidirectional Inductive Powering for Biomedical Implants*,

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

B. Lenaerts, R. Puers, *Omnidirectional Inductive Powering for Biomedical Implants*,

List of Symbols

α	load factor, $= \omega C_2 R_L$
δ	skin depth, penetration depth
$\tan\delta$	loss tangent, $= \frac{1}{Q}$
ϵ	electric permittivity
ϵ_0	$8.854 \cdot 10^{12}$ F/m, electric permittivity of free space
ϵ_r	relative electric permittivity
ζ	normalised time derivative of the switch voltage at switch opening
η	link efficiency
$\eta_{DC/AC}$	inverter efficiency
η_{rect}	rectifier efficiency
θ	spherical coordinate (Fig. 5.9)
λ	wavelength
μ	magnetic permeability
μ_0	$4\pi \cdot 10^{-7}$ H/m, magnetic permeability of free space
μ_r	relative magnetic permeability
ρ	free charge density
σ	electric conductivity
ϕ	magnetic flux
φ	spherical and cylindrical coordinate
ψ	phase difference
ω	angular frequency ($= 2\pi f$)
ω_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_φ	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_φ	out-of-plane electric field in an axisymmetric geometry, amplitude (phasor) or DC value
$\mathbf{E_c}$	conservative electric field component

B. Lenaerts, R. Puers, *Omnidirectional Inductive Powering for Biomedical Implants*,

$\mathbf{E_m}$	magnetically induced, non-conservative electric field component
e	2.718...
f	frequency
f_0	(self-)resonance frequency of an LC tank
$\mathbf{H}$	magnetic field
$\mathbf{I}$	current vector of a multi-port network containing all current phasors
I	current amplitude (phasor) or DC value
i	current in time domain
$\mathbf{J}$	conduction current density
$\mathbf{J^e}$	external source current density
J_φ	out-of-plane electric current density in an axisymmetric geometry, amplitude (phasor) or DC value
J_φ^e	out-of-plane external source current density in an axisymmetric geometry, amplitude (phasor) or DC value
J_z^e	out-of-plane external source current density in a 2-D model, amplitude (phasor) or DC value
k	coupling coefficient, $= \frac{M}{\sqrt{L_1 L_2}}$
L	self-inductance
L_0	one-turn equivalent self-inductance, $= \frac{L}{N^2}$
L_s	parasitic series inductance of a switch
L'	effective self-inductance of an LRC network
l	length
M	mutual inductance
M_0	one-turn equivalent mutual inductance, $= \frac{M}{N_1 N_2}$
N	number of turns of a winding
$\mathbf{\hat{n}}$	unity vector perpendicular to a boundary
n	square root of the inductance ratio of two coupled coils, $= \sqrt{\frac{L_2}{L_1}}$
$\mathbf{P}$	orientation vector of a sole secondary coil
P	power
$p_{R_{ON}}$	normalised conduction losses due to R_{ON}
p_{t_f}	normalised turn-off losses due to finite fall time t_f
p_{L_s}	normalised switching losses due to series inductance L_s
Q	quality factor
R	resistance
R_0	one-turn equivalent resistance, $= \frac{R}{N^2}$
R'	effective series resistance of an LRC network
R_{eq}	equivalent resistance seen at the primary side of an inductive link due to the coupled secondary circuit
R_{CC}	equivalent DC resistance seen at the input of an inverter
R_{DC}	equivalent load resistance connected to the output of a rectifier
R_L	equivalent secondary load resistance
R_{sys}	equivalent load resistance posed by the remote electronic system
r	cylindrical coordinate
S	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