TRANSFORMER AND INDUCTOR DESIGN HANDBOOK

Third Edition, Revised and Expanded

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Library of Congress Cataloging-in-Publication Data
A catalog record for this book is available from the Library of Congress.

ISBN: 0-8247-5393-3

This book is printed on acid-free paper.

Headquarters
Marcel Dekker, Inc.
270 Madison Avenue, New York, NY 10016, U.S.A.
tel: 212-696-9000; fax: 212-685-4540

Distribution and Customer Service
Marcel Dekker, Inc.
Cimarron Road, Monticello, New York 12701, U.S.A.
tel: 800-228-1160; fax: 845-796-1772

Eastern Hemisphere Distribution
Marcel Dekker AG
Hutgasse 4, Postfach 812, CH-4001 Basel, Switzerland
tel: 41-61-260-6300; fax: 41-61-260-6333

World Wide Web
http://www.dekker.com

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Current printing (last digit):

10 9 8 7 6 5 4 3 2 1

PRINTED IN THE UNITED STATES OF AMERICA

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To My Wife, Bonnie

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Foreword

Colonel McLyman is a well-known author, lecturer, and magnetic circuit designer. His previous books on transformer and inductor design, magnetic core characteristics, and design methods for converter circuits have been widely used by magnetics circuit designers.

In this book, Colonel McLyman has combined and updated the information found in his previous books. He has also added several new subjects such as rotary transformer design, planar transformer design, and planar construction. The author covers magnetic design theory with all of the relevant formulas along with complete information on magnetic materials and core characteristics. In addition, he provides real-world, step-by-step design examples.

This book is a must for engineers working in magnetic design. Whether you are working on high "rel" state-of-the-art design or high-volume or low-cost production, this book is essential. Thanks, Colonel, for a well-done, useful book.

Robert G. Noah
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Preface

I have had many requests to update *Transformer and Inductor Design Handbook*, because of the way power electronics has changed over the past few years. This new edition includes 21 chapters, with new topics such as: The forward converter, flyback converter, quiet converter, rotary transformers, and planar transformers, with even more design examples than the previous edition.

This book offers a practical approach, with design examples for design engineers and system engineers in the electronics and aerospace industries. Transformers are found in virtually all electronic circuits. This book can easily be used to design lightweight, high-frequency aerospace transformers or low-frequency commercial transformers. It is, therefore, a design manual.

The conversion process in power electronics requires the use of transformers, components that frequently are the heaviest and bulkiest item in the conversion circuit. Transformer components also have a significant effect on the overall performance and efficiency of the system. Accordingly, the design of such transformers has an important influence on overall system weight, power conversion efficiency, and cost. Because of the interdependence and interaction of these parameters, judicious trade-offs are necessary to achieve design optimization.

Manufacturers have, for years, assigned numeric codes to their cores to indicate their power-handling ability. This method assigns to each core a number called the area product, A_p, that is the product of its window area, W_a, and core cross-section area, A_c. These numbers are used by core suppliers to summarize dimensional and electrical properties in their catalogs. The product of the window area, W_a, and the core area, A_c, gives the area Product, A_p, a dimension to the fourth power. I have developed a new equation for the power-handling ability of the core, the core geometry, K_g. K_g has a dimension to the fifth power. This new equation provides engineers with faster and tighter control of their design. It is a relatively new concept, and magnetic core manufacturers are now beginning to include it in their catalogs.

Because of their significance, the area product, A_p, and the core geometry, K_g, are treated extensively in this handbook. A great deal of other information is also presented for the convenience of the designer. Much of the material is in tabular form to assist the designer in making the trade-offs best suited for a particular application in a minimum amount of time.

Designers have used various approaches in arriving at suitable transformer and inductor designs. For example, in many cases a rule of thumb used for dealing with current density is that a good working level is 1000 circular mils per ampere. This is satisfactory in many instances; however, the wire size used to meet this requirement may produce a heavier and bulkier inductor than desired or required. The information

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presented here will make it possible to avoid the use of this and other rules of thumb, and to develop a more economical and better design. While other books are available on electronic transformers, none of them seems to have been written with the user's viewpoint in mind. The material in this book is organized so that the student engineer or technician—starting at the beginning of the book and continuing through the end—will gain a comprehensive knowledge of the state of the art in transformer and inductor design.

No responsibility is assumed by the author or the publisher for any infringement of patent or other rights of third parties that may result from the use of circuits, systems, or processes described or referred to in this handbook.

Acknowledgments

In gathering the material for this book, I have been fortunate in having the assistance and cooperation of several companies and many colleagues. I wish to express my gratitude to all of them. The list is too long to mention them all. However, there are some individuals and companies whose contributions have been especially significant. Colleagues who have retired from Magnetics include Robert Noah and Harry Savisky, who helped so greatly with the editing of the final draft. Other contributions were made by my colleagues at Magnetics, Lowell Bosley and his staff for sending up-to-date catalogs and sample cores. I would like to thank colleagues at Micrometals Corp., Jim Cox and Dale Nicol, and George Orenchak of TSC International. I would like to give special thanks to Richard (Oz) Ozenbaugh of Linear Magnetics Corp. for his assistance in the detailed derivations of many of the equations and his efforts in checking the design examples. I also give special thanks to Steve Freeman of Rodon Products, Inc., for building and testing the magnetics components used in the design examples.

I am also grateful to: Dr. Vatche Vorperian of Jet Propulsion Laboratory (JPL) for his help in generating and clarifying equations for the Quiet Converter; Jerry Fridenberg of Fridenberg Research, Inc., for modeling circuits on his SPICE program; Dr. Gene Wester of JPL for his input; and Kit Sum for his assistance in the energy-storage equations. I also thank the late Robert Yahiro for his help and encouragement over the years.

Colonel Wm. T. McLyman

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About the Author

Colonel Wm. T. McLyman recently retired as a Senior Member of the Avionics Equipment Section of the Jet Propulsion Laboratory (JPL) affiliated with the California Institute of Technology in Pasadena, California. He has 47 years of experience in the field of Magnetics, and holds 14 United States Patents on magnetics-related concepts. Through his 30 years at JPL, he has written over 70 JPL Technical Memorandums, New Technology Reports, and Tech-Briefs on the subject of magnetics and circuit designs for power conversion. He has worked on projects for NASA including the Pathfinder Mission to Mars, Cassini, Galileo, Magellan, Viking, Voyager, MVM, Hubble Space Telescope, and many others.

He has been on the lecture circuit for over 20 years speaking in the United States, Canada, Mexico, and Europe on the design and fabrication of magnetic components. He is known as a recognized authority in magnetic design. He is currently the President of his own company, Kg Magnetics, Inc., which specializes in power magnetics design.

He recently completed a book entitled, *High Reliability Magnetic Devices: Design and Fabrication* (Marcel Dekker, Inc.). He also markets, through Kg Magnetics, Inc., a magnetics design and analysis software computer program called "Titan" for transformers and inductors (see Figure 1). This program operates on Windows 95, 98, 2000, and NT.

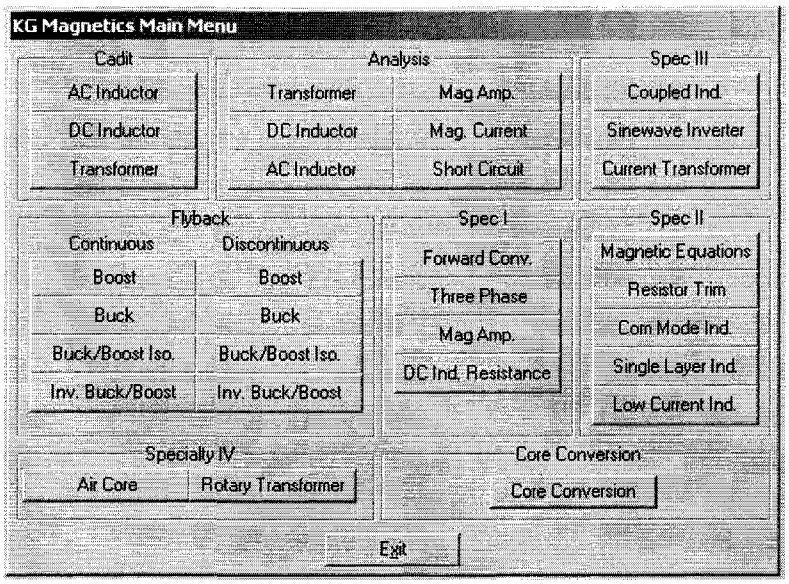

Figure 1. Computer Design Program Main Menu.

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Derivations for the Design Equations

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Symbols

α	regulation, %
A_c	effective cross section of the core, cm^2
A_p	area product, cm^4
A_t	surface area of the transformer, cm^2
A_w	wire area, cm^2
$A_{w(B)}$	bare wire area, cm^2
$A_{w(I)}$	insulated wire area, cm^2
A_{wp}	primary wire area, cm^2
A_{ws}	secondary wire area, cm^2
A-T	amp turn
AWG	American Wire Gage
B	flux, tesla
B_{ac}	alternating current flux density, tesla
ΔB	change in flux, tesla
B_{dc}	direct current flux density, tesla
B_m	flux density, tesla
B_{max}	maximum flux density, tesla
B_o	operating peak flux density, tesla
B_{pk}	peak flux density, tesla
B_r	residual flux density, tesla
B_s	saturation flux density, tesla
C	capacitance
C_n	new capacitance
C_p	lumped capacitance
CM	circular mils
D_{AWG}	wire diameter, cm
$D_{(min)}$	minimum duty ratio
$D_{(max)}$	maximum duty ratio
D_x	dwell time duty ratio
E	voltage
E_{Line}	line to line voltage
E_{Phase}	line to neutral voltage
Energy	energy, watt-second

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ESR	equivalent series resistance
η	efficiency
f	frequency, Hz
F	fringing flux factor
F_m	magneto-motive force, mmf
F.L.	full load
G	winding length, cm
γ	density, in grams-per-cm^2
ε	skin depth, cm
H	magnetizing force, oersteds
H_c	magnetizing force required to return flux to zero, oersteds
ΔH	delta magnetizing force, oersteds
H_o	operating peak magnetizing force
H_s	magnetizing force at saturation, oersteds
I	current, amps
I_c	charge current, amps
ΔI	delta current, amps
I_{dc}	dc current, amps
I_{in}	input current, amps
I_{Line}	input line current, amps
I_{Phase}	input phase current, amps
I_m	magnetizing current, amps
I_o	load current, amps
$I_{o(max)}$	maximum load current, amps
$I_{o(min)}$	minimum load current, amps
I_p	primary current, amps
I_s	secondary current, amps
$I_{s(Phase)}$	secondary phase current, amps
$I_{s(Line)}$	secondary line current, amps
J	current density, amps per cm^2
K_c	copper loss constant
K_c	quasi-voltage waveform factor
K_e	electrical coefficient

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K_f	waveform coefficient
K_g	core geometry coefficient, cm^5
K_j	constant related to current density
K_s	constant related to surface area
K_u	window utilization factor
K_{up}	primary window utilization factor
K_{us}	secondary window utilization factor
K_{vol}	constant related to volume
K_w	constant related to weight
L	inductance, henry
L_c	open circuit inductance, henry
L_p	primary inductance, henry
l	is a linear dimension
$L_{(crt)}$	critical inductance
λ	density, grams per cm^3
l_g	gap, cm
l_m	magnetic path length, cm
l_t	total path length, cm
mks	meters-kilogram-seconds
MLT	mean length turn, cm
mmf	magnetomotive force, F_m
MPL	magnetic path length, cm
mW/g	milliwatts-per-gram
μ	permeability
μ_i	initial permeability
μ_Δ	incremental permeability
μ_m	core material permeability
μ_o	permeability of air
μ_r	relative permeability
μ_e	effective permeability
n	turns ratio
N	turns
N.L.	no load

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N_L	inductor turns
N_n	new turns
N_p	primary turns
N_s	secondary turns
P	watts
P_{cu}	copper loss, watts
P_{fe}	core loss, watts
P_g	gap loss, watts
ϕ	magnetic flux
P_{in}	input power, watts
P_L	inductor copper loss, watts
P_o	output power, watts
P_p	primary copper loss, watts
P_s	secondary copper loss, watts
P_Σ	total loss (core and copper), watts
P_t	total apparent power, watts
P_{VA}	primary volt-amps
R	resistance, ohms
R_{ac}	ac resistance, ohms
R_{cu}	copper resistance, ohms
R_{dc}	dc resistance, ohms
R_e	equivalent core loss (shunt) resistance, ohms
R_g	reluctance of the gap
R_m	reluctance
R_{mt}	total reluctance
R_o	load resistance, ohms
$R_{o(R)}$	reflected load resistance, ohms
$R_{in(equiv)}$	reflected load resistance, ohms
R_p	primary resistance, ohms
R_R	ac/dc resistance ratio
R_s	secondary resistance, ohms
R_t	total resistance, ohms
ρ	resistivity, ohm-cm

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S_1	conductor area/wire area
S_2	wound area/usable window
S_3	usable window area/window area
S_4	usable window area/usable window area + insulation area
S_{np}	number of primary strands
S_{ns}	number of secondary strands
S_{VA}	secondary volt-amps
T	total period, seconds
t_{off}	off time, seconds
t_{on}	on time, seconds
t_w	dwell time, seconds
T_r	temperature rise, °C
U	multiplication factor
VA	volt-amps
V_{ac}	applied voltage, volts
V_c	control voltage, volts
$V_{c(pk)}$	peak voltage, volts
V_d	diode voltage drop, volts
V_{in}	input voltage, volts
$V_{in(max)}$	maximum input voltage, volts
$V_{in(min)}$	minimum input voltage, volts
V_n	new voltage, volts
V_o	output voltage, volts
V_p	primary voltage, volts
$V_{p(rms)}$	primary rms voltage, volts
$V_{s(LL)}$	secondary line to line voltage, volts
$V_{s(LN)}$	secondary line to neutral voltage, volts
$V_{r(pk)}$	peak ripple voltage
V_s	secondary voltage, volts
ΔV_{CC}	capacitor voltage, volts
ΔV_{CR}	capacitor ESR voltage, volts
ΔV_p	delta primary voltage, volts
ΔV_s	delta secondary voltage, volts

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W	watts
W/kg	watts-per-kilogram
W_a	window area, cm^2
W_{ap}	primary window area, cm^2
W_{as}	secondary window area, cm^2
$W_{a(eff)}$	effective window area, cm^2
w-s	watt-seconds
W_t	weight, grams
W_{tcu}	copper weight, grams
W_{tfe}	iron weight, grams
X_L	inductive reactance, ohms

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