Power Systems

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Principles and Applications

With 220 Figures

Springer

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Preface

This book on pulsed power systems is the result of a course that I have been teaching for ten years at the Technical University of Karlsruhe. Initially planned as a course for German students, it became part of the courses offered to foreign students from all over the world in the International Department of the University in 1998. The book should provide students beginning in this field with the necessary background to explore the more advanced literature. In a similar way, it should also serve to help engineers and scientists from other fields to become familiar with the basic ideas and methods of pulsed power and to achieve a sound judgement of its potential usefulness for solving their problems. The main characteristic of pulsed power is the very high peak-to-average power ratio. Therefore it can exploit threshold and nonlinear effects. Another set of benefits can result from the short pulse duration, which allows one to exploit the time domain (e.g. in radar and flash X-ray radiography) or to avoid competing processes (e.g. electric breakdown or heat losses). Pulsed-power methods have fertilised many disciplines in electrical engineering, experimental physics, biotechnology, food technology and material science.

When I started the course on pulsed power in 1995, I realised the lack of an introductory textbook. Although a collection of unpublished technical papers emanating from the work of J.C. Martin at Aldermaston in the 1960s and 1970s on nanosecond intense flash X-ray sources for radiography was in common use at many pulsed-power laboratories, this was not an adequate substitute for a textbook. This situation did not change when, in 1996, T. Martin, A. Guenther, and M. Kristiansen published J.C. Martin's papers in a book entitled *J.C. Martin, On Pulsed Power*. Nevertheless, many of the empirical formulae derived by J.C. Martin are still very useful in designing pulsed-power systems and have been reproduced in the present book, generally keeping the original practical units.

The ideal textbook will never be completed. New and exciting developments appear continuously, and the reader is referred to the digests of technical papers of the biannual series of the IEEE International Pulsed Power Conferences, the records of the Power Modulator Symposia, and the proceedings of the International Conferences on High-Power Particle Beams for the latest advancements.

For many years, the majority of new developments in pulsed power appeared in the USA, and the IEEE International Pulsed Power Conferences, held since 1976 exclusively in the USA, underline this statement. Also, I took my first steps in this field during a stay at Cornell University, New York State, in 1980, where at that time the new discipline of collective pulsed ion beams was coming into existence. After the fall of the Iron Curtain, however, it became apparent that an equally large advancement in pulsed power had been made in the former Soviet Union. Although many of the objectives were purely military, some very fruitful innovations for civil applications became disclosed too, triggering a number of successful civil programmes, especially in Japan and Europe, but also at several universities in the US. Recently, the new discipline of bioelectrics, whose subject is the study of the interaction between strong pulsed electric fields and biological cells, has grown rapidly in the USA (Old Dominion University, Norfolk, Virginia), Japan (Kumamoto University, Kyushu Island), Germany (Forschungszentrum Karlsruhe), and other countries. It is fair to say that the selection of the topics of the chapters of this book on applications leans mainly towards my own interests and those of my research group in the Institute for Pulsed Power and Microwave Technology at Forschungszentrum Karlsruhe.

Although the largest part of this book was worked on during weekends and evenings, a six-month stay as a visiting professor at Kumamoto University in 2003 accelerated its completion. Therefore, I am very grateful to H. Akiyama for his kind invitation. Pulsed-power science at Forschungszentrum Karlsruhe would never have been possible without the initiative of G. Kessler in 1979 to begin an intense light-ion-beam programme for inertial fusion energy at the Institute of Neutron Physics and Reactor Technology. Soon after his retirement in 1999, it was decided to stop the light-ion-beam programme in Karlsruhe. As frequently happens in scientific research, a crisis brings with it the chance of a new beginning, and I am thankful to M. Thumm that he constantly supported our new approaches towards industrial applications of pulsed power in the newly founded Institute for Pulsed Power and Microwave Technology. The book comes with a CD containing the very useful transmission line code LEITER, written by my former colleague D. Rusch, whom I would like to thank for his agreement to include the program in the book. Also, I would like to thank my colleagues W. An, K. Baumung, W. Frey, H. Giese, P. Hoppé, G. Müller, M. Sack, C. Schultheiß and A. Weisenburger, whose expertise in pulsed power entered into this book.

My wife Ursula certainly suffered a lot during the finalisation of this book, which often prevented joint activities at weekends, and I am very grateful for her patience. Now it's done.

Karlsruhe, March 2006 *Hansjoachim Bluhm*

Contents

Symbols and Abbreviations

Symbols

$\vec{A}$	vector potential; vectorial element of area
A	area
$\vec{B}$	magnetic induction
C	capacitance; 0.577 (Eulerian constant)
c	velocity of light
c_{v}	specific heat per unit mass
$\vec{D}$	displacement
d	distance
$\vec{E}$	electric field
e	elementary charge
$\vec{F}$	force
$F(E,t)$	probability of failure at time t and field stress E
$F(W)$	Fermi–Dirac function at energy W
G	conductance; shear modulus
$G(p)$	transfer function
$G_{\mathrm{n,p}}$	generation rates of electrons and holes
g	geometric factor
$\vec{H}$, H	magnetic field strength
H	Hamiltonian function
$H(t)$	Heaviside function
h	Planck's constant; thickness
I	current
I_0	total current in vacuum line
I_α	Alfvén current
I_{cr}	critical current
I_{w}	wall current
i	imaginary unit $\sqrt{-1}$

$i(p)$	Laplace- or Fourier-transformed current
$i(t)$	small-signal current
J	current density integral
j	current density
K	Kerr constant
k	Boltzmann constant; mobility
$k_\pm$	constants
L	inductance
L_d	diffusion length
ℓ	length
M	macroscopic mass
m	particle mass
m_0	particle rest mass
N	total number of particles
n	number of atoms per unit volume
$\vec{P}$	canonical momentum
P	polarisation
P_al	matched-load power
P_ab	transition probability from state a to b
p	gas pressure; Laplace operator
Q	heat energy; specific energy density; electron charge per unit length of vacuum line
q	surface charge density
R	resistance
$R_\mathrm{n,p}$	recombination rates of electrons and holes
r	radius
$\vec{S}$	Poynting vector
S	general stress parameter
s	channel length; path length
T	period; transit time; transmission coefficient; temperature
t	time
U	voltage
u	velocity
$u(p)$	Laplace-transformed voltage
$u(t)$	small-signal voltage
$\langle u\rangle$	mean swarm velocity
V	volume; Verdet constant
W_+, W_-	energy levels

W_{kin}	kinetic energy
w_{kin}	kinetic-energy density
x	spatial coordinate
Y	Young's modulus
Z	impedance
$Z(W)$	number of allowed states per unit energy interval at W
α	ionisation coefficient
α_{n}, α_{p}	ionisation coefficients for electrons and holes in a semiconductor
β	$u/c =$ particle velocity relative to the velocity of light; field enhancement factor
$\mathit{\Gamma}$	gamma function
γ	ω/α; relativistic factor
δ	maximum stress/mean stress; detachment coefficient
$\delta_{\mathit{\Phi}}$	magnetic-flux skin depth
$\mathrm{tg}\,\delta$	loss factor
ε	relative dielectric constant
ε_0	permittivity of free space
ζ	surface energy
η	efficiency; electron attachment coefficient
$\mathit{\Theta}$	moment of inertia
$\mathit{\Lambda}_{\mathrm{ab}}$	reconfiguration energy
λ	mean free path between collisions; thermal conductivity
μ	relative permeability; mobility
μ_0	permeability of free space
μ_{n}, μ_{p}	electron and hole mobilities in a semiconductor
ν	frequency
ν_{ei}	electron–ion collision frequency
$\xi(S)$	relative expected failure rate at stress S
$\mathit{\Pi}$	Paschen function
ρ	reflection coefficient
$\mathit{\Sigma}$	macroscopic cross-section
$\mathit{\Sigma}_{\mathrm{y}}$	yield strength
σ	tensile strength; microscopic cross-section; conductivity; variance
σ_{a}	standard deviation
τ	time constant; time between collisions
$\mathit{\Phi}$	magnetic flux
φ	potential; work function

χ	ratio of specific heats
$\psi(S)$	survival probability at stress S
ω	angular frequency; secondary-electron emission coefficient

Abbreviations

ADP	ammonium dihydrogen phosphate
ADS	accelerator-driven reactor system
CVR	current-viewing resistor
DIN	Deutsche Industrienorm (German Industry Standard)
DSRD	drift step recovery diode
EMHD	electron magnetohydrodynamics
FRANKA	Fragmentierungsanlage Karlsruhe (Fragmentation Device, Karlsruhe)
FWHM	full width at half maximum
GESA	gepulste Elektronenstrahlenanlage (Pulsed-Electron-Beam Facility)
GTO	gate turn-off thyristor
GW	gigawatt
Gy	Gray, unit of radiation dose
HELIA	high-energy linear induction accelerator
IFE	inertial-fusion energy
IGBT	insulated-gate bipolar transistor
IHL	inner Helmholtz layer
KALIF	Karlsruhe light-ion facility
KDP	potassium dideuterium phosphate
KEA	Karlsruher Elektroporations Anlage (Karlsruhe Electroporation Facility)
MS	magnetic switch
OHL	outer Helmholtz layer
PBFA	particle beam fusion accelerator
PEF	pulsed electric field
PFL	pulse-forming line
PIC	particle in cell
POS	plasma opening switch
RHEPP	repetitive high-energy pulsed power
RLD	region of low density
SCR	silicon-controlled rectifier
SOS	semiconductor opening switch

SPT	self-pinched transport
SRD	step recovery diode
TBC	thermal barrier coating
TE	transverse electric (H-mode)
TGO	thermally grown oxide scale
TM	transverse magnetic (E-mode)
TVG	triggered vacuum gap
TW	terawatt
YSZO	yttria-stabilised zirconia