Power Electronics and Motor Drives

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Advances and Trends

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ABOUT THE AUTHOR

Dr. Bimal K. Bose (*Life Fellow, IEEE*) has held the Condra Chair of Excellence in Power Electronics at the University of Tennessee, Knoxville, since 1987. Prior to this, he was a research engineer at General Electric Corporate Research and Development (now GE Global Research Center) in Schenectady, New York (1976–1987), faculty member at Rensselaer Polytechnic Institute, Troy, New York (1971–1976), and faculty member of Bengal Engineering and Science University (formerly Bengal Engineering College) for 11 years. He has done extensive research in power electronics and motor drive areas, including converters, PWM techniques, microcomputer/DSP control, motor drives, and application of expert systems, fuzzy logic, and neural networks to power electronic systems. He has authored or edited seven books, published more than 190 papers, and holds 21 U.S. patents. He has given invited presentations, tutorials, and keynote addresses throughout the world. He is a recipient of a number of awards and honors that include the IEEE Power Electronics Society William E. Newell Award (2005), IEEE Millennium Medal (2000), IEEE Meritorious Achievement Award in Continuing Education (1997), IEEE Lamme Gold Medal (1996), IEEE Industrial Electronics Society Eugene Mittelmann Award for lifetime achievement in power electronics (1994), IEEE Region 3 Outstanding Engineer Award (1994), IEEE Industry Applications Society Outstanding Achievement Award (1993), General Electric Silver Patent Medal (1986) and Publication Award (1987), and the Calcutta University Mouat Gold Medal (1970).

PREFACE

I am presenting this novel book on advances and trends in power electronics and motor drives to the professional community with the expectation that it will be given the same wide and enthusiastic acceptance by practicing engineers, R&D professionals, university professors, and even graduate students that my other books in this area have. Unlike the traditional books available in the area of power electronics, this book has a unique presentation format that makes it convenient for group presentations that use Microsoft's PowerPoint software. In fact, a disk is included that has a PowerPoint file on it that is ready for presentation with the core figures. Presentations can also be organized using just selected portions of the book.

As you know, power electronics and motor drive technology is very complex and multidisciplinary, and it has gone through a dynamic evolution in recent years. Power electronics engineers and researchers are having a lot of difficulty keeping pace with the rapid advancements in this technology. This book can be looked on as a text for a refresher or continuing education course for those who need a quick review of recent technological advancements. Of course, for completeness of the subject, the core technology is described in each chapter. A special feature of the book is that many examples of recent industrial applications have been included to make the subject interesting. Another novel feature is that a separate chapter has been devoted to the discussion of typical questions and answers.

During the last 40+ years of my career in the industrial and academic environment, I have accumulated vast amounts of experience in the area of power electronics and motor drives. Besides my books, technical publications, and U.S. patents, I have given tutorials, invited presentations, and keynote addresses in different countries around the world at many IEEE as well as non-IEEE conferences. A mission in my life has been to promote power electronics globally. I hope that I have been at least partially successful. I pursued the advancement of power electronics technology aggressively from its beginning and have tried to present my knowledge and experience in the whole subject for the benefit of the professional community. However, the book should not be considered as a first or second course in power electronics. The reader should have a good background in the subject to assimilate the content of the book.

Each page contains one or more figures or a bulleted chart with explanations given below it—just like a tutorial presentation. The bulk of the figures are taken from my personal presentation materials from tutorials, invited seminars, and class notes. A considerable amount of material is also taken from my other publications, including the published books.

Unlike a traditional text, the emphasis is on physical explanation rather than mathematical analysis. Of course, exceptions have been made where it is absolutely necessary. After description of the core material in each chapter, the relevant advances and trends are given from my own experience and perspective. For further digging into the subject, selected references have been included at the end of each chapter. I have not seen a similar book in the literature. With its novel and unique presentation format, I describe it as a 21st-century book on power electronics. If opportunity arises, I will create a complete video course on the entire subject in the near future.

The content of the book has been organized to cover practically the entire field of power electronics. Chapter 1 gives a broad introduction and perspective on importance and applications of the technology. Chapter 2 describes modern power semiconductor devices that are viable in industrial applications. Chapter 3 deals with the classical power electronics, including phase-controlled converters and cycloconverters, which are still very important today. Chapter 4 describes voltage-fed converters, which are the most important type of converter in use today and will remain so tomorrow. The chapter includes a discussion of different PWM techniques, static VAR compensators, and active filters. Chapter 5 describes current-fed converters, which have been used in relatively large power applications. Chapter 6 describes different types of ac machines for variable-frequency drives. Chapter 7 deals with control and estimation techniques for induction motor drives, whereas Chapter 8 deals with control and estimation techniques for synchronous motor drives. Chapter 9 covers simulation and digital control in power electronics, including modern microcomputers and DSPs. The content of this chapter is somewhat new and very important. Chapter 10 describes fuzzy logic principles and their applications, and Chapter 11 provides comprehensive coverage of artificial neural networks and their applications. Finally, Chapter 12 poses some selected questions and their answers which are typical after any tutorial presentation.

This book could not have been possible without active contributions from several of my professional colleagues, graduate students, and visiting scholars in my laboratory. The most important contribution came from Lu Qiwei, a graduate student of China University of Mining and Technology (CUMT), Beijing, China, who devoted a significant amount of time to preparing a large amount of the artwork for this book. Professor Joao Pinto of the Federal University of Mato Grosso do Sul (UFMS) in Brazil made significant contributions to the book in that he prepared the demonstration programs in fuzzy logic and neural network applications. I also acknowledge the help of his graduate students. Dr. Wang Cong of CUMT provided help in preparation of the book. Dr. Kaushik Rajashekara of Rolls-Royce gave me a lot of ideas for the book and worked hard in checking the manuscript. Dr. Hirofumi Akagi of the Tokyo Institute of Technology, Japan, gave me valuable advice. Dr. Marcelo Simoes of the Colorado School of Mines and Ajit Chattopadhyay of Bengal Engineering and Science University, India, also deserve thanks for their help. Finally, I would like to thank my graduate students and visiting scholars for their outstanding work, which made the book possible. Some of them are Drs. Marcelo Simoes; Jason Lai of Virginia Tech; Luiz da Silva of Federal University of Itajuba, Brazil; Gilberto Sousa of Federal University of Espirito Santo, Brazil; Wang Cong; Jin Zhao of Huazhong University of Science and Technology, China; M. H. Kim of Yeungnam College of Science & Technology, Korea; and Nitin Patel of GM Advanced Technology Vehicles. In my opinion, they are the best scholars in the world—it is often said that great graduate students and visiting scholars make the professor great. I am also thankful to the University of Tennessee for providing me with opportunities to write this book. Finally, I acknowledge the immense patience and sacrifice of my wife Arati during preparation of the book during the past 2 years.

Bimal K. Bose
June 2006

LIST OF VARIABLES AND SYMBOLS

d^e-q^e	Synchronously rotating reference frame direct and quadrature axes
d^s-q^e	Stationary reference frame direct and quadrature axes (also known as α-β axes)
f	Frequency (Hz)
I_d	dc current (A)
I_f	Machine field current
I_L	rms load current
I_m	rms magnetizing current
I_P	rms active current
I_Q	rms reactive current
I_r	Machine rotor rms current (referred to stator)
I_s	rms stator current
$i_{dr}{}^s$	d^s axis rotor current
$i_{ds}{}^s$	d^s axis stator current
i_{dr}	d^e axis rotor current (referred to stator)
i_{qr}	q^e axis rotor current (referred to stator)
i_{qs}	q^e axis stator current
J	Rotor moment of inertia (kg-m^2)
X_r	Rotor reactance (referred to stator) (ohm)
X_s	Synchronous reactance
X_{ds}	d^e axis synchronous reactance
X_{lr}	Rotor leakage reactance (referred to stator)
X_{ls}	Stator leakage reactance
X_{qs}	q^e axis synchronous reactance

α	Firing angle
β	Advance angle
γ	Turn-off angle
δ	Torque or power angle of synchronous machine
θ	Thermal impedance (Ohm); also torque angle
θ_e	Angle of synchronously rotating frame ($\omega_e t$)
θ_r	Rotor angle
θ_{sl}	Slip angle ($\omega_{sl} t$)
μ	Overlap angle
τ	Time constant (s)
L_c	Commutating inductance (H)
L_d	dc link filter inductance
L_m	Magnetizing inductance
L_r	Rotor inductance (referred to stator)
L_s	Stator inductance
L_{lr}	Rotor leakage inductance (referred to stator)
L_{ls}	Stator leakage inductance
L_{dm}	d^e axis magnetizing inductance
L_{qm}	q^e axis magnetizing inductance
m	PWM modulation factor for SPWM ($m = 1.0$ at undermodulation limit, i.e., $m' = 0.785$)
m'	PWM modulation factor, where $m' = 1$ at square wave
p	Number of poles
P	Active power
P_g	Airgap power (W)
P_m	Mechanical output power
Q	Reactive power
R_r	Rotor resistance (referred to stator)
R_s	Stator resistance
S	Slip (per unit)

T	Time period(s); also temperature (°C)
T_e	Developed torque (Nm)
T_L	Load torque
t_{off}	Turn-off time
V_c	Counter emf
V_d	dc voltage
V_I	Inverter dc voltage
V_f	Induced emf
V_m	Peak phase voltage (V)
V_g	rms airgap voltage
V_R	Rectifier dc voltage
v_s	Instantaneous supply voltage
v_d	Instantaneous dc voltage
v_f	Instantaneous field voltage
$v_{dr}{}^s$	d^s axis rotor voltage (referred to stator)
$v_{ds}{}^s$	d^s axis stator voltage
v_{dr}	d^e axis rotor voltage (referred to stator)
v_{qr}	q^e axis rotor voltage (referred to stator)
v_{qs}	q^e axis stator voltage
φ	Displacement power factor angle
ψ_a	Armature reaction flux linkage (Weber-turns)
ψ_f	Field flux linkage
ψ_m	Airgap flux linkage
ψ_r	Rotor flux linkage
ψ_s	Stator flux linkage
$\psi_{dr}{}^s$	d^s axis rotor flux linkage (referred to stator)
$\psi_{ds}{}^s$	d^s axis rotor flux linkage
ψ_{dr}	d^e axis rotor flux linkage (referred to stator)
ψ_{qr}	q^e axis rotor flux linkage (referred to stator)

ψ_{qs}	q^e axis stator flux linkage
ω_e	Stator or line frequency ($2\pi f$) (rad/s)
ω_m	Rotor mechanical speed
ω_r	Rotor electrical speed
ω_{sl}	Slip frequency
$\hat{X}$	Peak value of a sinusoidal phasor or sinusoidal space vector magnitude; also estimated parameter, where X is any arbitrary variable
$\bar{X}$	Space vector variable; also designated by the peak value $\hat{X}$ where it is a sinusoid