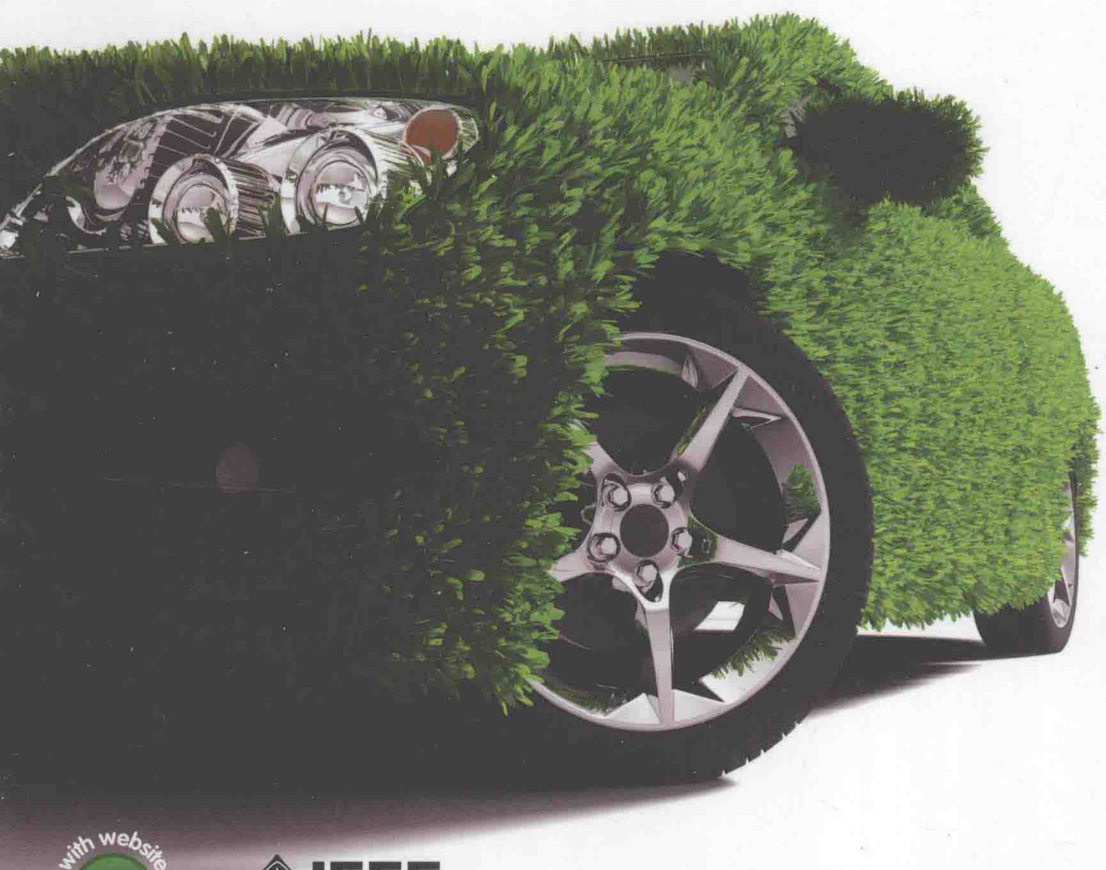
ELECTRIC VEHICLE MACHINES AND DRIVES

DESIGN, ANALYSIS AND APPLICATION

K. T. CHAU



with website

IEEE
IEEE PRESS

WILEY

ELECTRIC VEHICLE MACHINES AND DRIVES

DESIGN, ANALYSIS AND APPLICATION

K. T. Chau

International Research Centre for Electric Vehicles
The University of Hong Kong

IEEE

WILEY

This edition first published 2015

Registered office
John Wiley & Sons Singapore Pte. Ltd., 1 Fusionopolis Walk, #07-01 Solaris South Tower, Singapore 138628.

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com.

Library of Congress Cataloging-in-Publication Data applied for.

ISBN 978-1-118-75252-4

Typeset in 9.5/11.5pt TimesLTStd by SPi Global, Chennai, India
Printed and bound in Singapore by Markono Print Media Pte Ltd

1 2015

Preface

Born in a metropolitan city, I have fully witnessed the decolorization of our blue sky over the past few decades. Hoping to contribute an effort to recover our blue sky, I have devoted myself to researching electric vehicle (EV) technologies for over 20 years – starting from my undergraduate final year project in EV battery monitoring in 1987 to my latest research project in EV in-wheel motor drives in 2014. In fact, EVs have been globally identified to be the greenest road transportation, and the use of EVs will be the most practical way to combat smog and soot from road vehicles in the foreseeable future.

Over the years, there have been many books dealing with EV technologies, mainly briefing various technologies in pure EVs, hybrid EVs, or fuel-cell EVs. Because of the multidisciplinary nature of EV technologies, it is hardly possible to embrace all of them in a single book without sacrificing the latest developments or in-depth discussions. In recent years, some books have begun to deal with specific EV technologies, such as electric propulsion, hybrid propulsion, batteries, and fuel cells. Although many EV machines and drives have been widely published as papers in learned journals, a book comprehensively discussing them is highly desirable. In fact, such advancement of machines and drives is beneficial to the whole EV trio – namely the pure, hybrid, and fuel-cell EVs.

The purpose of this book is to provide a comprehensive discussion on machines and drives for pure electric, hybrid, and fuel-cell vehicles, including both electric propulsion and hybrid propulsion. The corresponding motor drives for electric propulsion range from the existing types, namely the DC, induction, permanent magnet (PM) brushless, and switched reluctance motor drives, to the advanced types, namely the stator-PM, magnetic-geared, vernier PM, and advanced magnetless motor drives. The corresponding machine systems for hybrid propulsion cover the existing types, namely the integrated-starter-generator and planetary-geared electric variable transmission (EVT) systems, and the advanced types, namely the double-rotor EVT and magnetic-geared EVT systems. Meanwhile, emphasis is given to the design criteria, performance analyses, and application examples or potentials of various motor drives and machine systems. It is anticipated that various EVs will adopt different machines and drives, and this book will be a key reference for researchers, engineers, and administrators who need to make such decisions.

While EVs are the driving force for a better environment, my family is the driving power for my work on EVs. Especially, I would like to take this chance to express my heartfelt gratitude to my son, Aten Man-Ho, and my wife, Joan Wai-Yi, for their hearty support all the way.

K.T. Chau

Organization of This Book

This book provides a comprehensive knowledge of electric vehicle (EV) machines and drives, including latest developments and in-depth discussions. It is written for a wide coverage of readers including students, researchers, engineers, administrators, and general readers, and is organized into two themes:

- The first theme is the knowledge of various electric motor drives for EVs, including pure electric and fuel-cell vehicles. It is composed of eight chapters in which Chapters 2–5 deal with those available motor drives for existing EVs, while Chapters 6–9 discuss those advanced motor drives for future EVs.
- The second theme is the knowledge of various electric machine systems for hybrid electric vehicles (HEVs). It consists of four chapters in which Chapters 10 and 11 describe those available machine systems for existing HEVs, while Chapters 12 and 13 elaborate those advanced machine systems for future HEVs.

In this book, there are in total 13 chapters. Each chapter has different numbers of sections and subsections. In order to facilitate selection of reading, all chapters are outlined below:

- Chapter 1 gives an introduction of EVs, including the classification of EVs, overview of EV challenges, and overview of various technologies developed for EVs.
- Chapter 2 is devoted to discussing DC motor drives for EVs, including their system configurations, DC machines, DC-DC converters, and control strategies. The corresponding design criteria, design examples, and application examples are also mentioned.
- Chapter 3 is devoted to discussing induction motor drives for EVs, including their system configurations, induction machines, power inverters, and control strategies. The corresponding design criteria, design examples, and application examples are also discussed.
- Chapter 4 is devoted to discussing permanent magnet (PM) brushless motor drives for EVs, covering both the PM synchronous and PM brushless DC types. Their PM materials, system configurations, PM brushless machines, power inverters, and control strategies are described. The corresponding design criteria, design examples, and application examples are also discussed.
- Chapter 5 is devoted to discussing switched reluctance (SR) motor drives for EVs, including their system configurations, SR machines, SR converters, and control strategies. The corresponding design criteria, design examples, and application examples are also discussed.
- Chapter 6 discusses various stator-PM motor drives for EVs, embracing the doubly-salient PM, flux-reversal PM, flux-switching PM, hybrid-excited PM, and flux-mnemonic PM types. The corresponding design criteria, design examples, and potential applications are also given.
- Chapter 7 discusses magnetic-geared (MG) motor drives for EVs, including their system configurations, magnetic gears, MG machines, power inverters, and control strategies. The corresponding design criteria, design examples, and potential applications are also given.

- Chapter 8 discusses vernier PM motor drives for EVs, including their system configurations, vernier PM machines, power inverters, and control strategies. The corresponding design criteria, design examples, and potential applications are also given.
- Chapter 9 discusses various advanced magnetless motor drives for EVs, covering the synchronous reluctance, doubly-salient DC, flux-switching DC, vernier reluctance, doubly-fed vernier reluctance, and axial-flux magnetless types. The corresponding design criteria, design examples, and potential applications are also given.
- Chapter 10 describes integrated-starter-generator systems for HEVs, including their system configurations, machine structures, and operation modes. The corresponding design criteria, design examples, and application examples are also discussed.
- Chapter 11 describes planetary-geared electric variable transmission systems for HEVs, including the system configurations and planetary gears as well as the input-split and compound-split planetary-geared types. The corresponding design criteria, design example, and application examples are also mentioned.
- Chapter 12 describes double-rotor electric variable transmission systems for HEVs, including the system configurations and double-rotor machines as well as the basic and advanced double-rotor types. The corresponding design criteria, design example, and potential applications are also mentioned.
- Chapter 13 describes MG electric variable transmission systems for HEVs, including the system configurations and multi-port magnetic gears as well as the magnetic planetary-geared and magnetic concentric-geared types. The corresponding design criteria, design example, and potential applications are also briefed.

Readers have the flexibility of reading those chapters that are most interesting to them. The suggestion for reading is as follows:

- Undergraduate students taking a course dedicated to EV technologies may be particularly interested in Chapters 1–5 as well as Chapters 10 and 11.
- Postgraduate students taking a course dedicated to advanced EV technologies may be interested in all chapters.
- Researchers in the area of EV machines and drives may be interested in all chapters. Particularly, they may have special interest in Chapters 6–9 as well as Chapters 12 and 13, which involve newly explored research topics.
- Practicing engineers for product design and development may be more interested in Chapters 6–9 as well as Chapters 12 and 13 in which new ideas can be triggered and commercial products can be derived.
- Administrators and general readers may be interested in all chapters. They are advised to read the book from the beginning to the end, page by page, which is most enjoyable.

Acknowledgments

Material presented in this book is a collection of many years of research and development by the author in the International Research Centre for Electric Vehicles and the Department of Electrical and Electronic Engineering at The University of Hong Kong.

I am grateful to all members of my Electric Vehicle Technologies research group, especially Dr. Wenlong Li, Mr. Christopher Ho-Tin Lee, Mr. Mu Chen, Miss Fei Lin, Mr. Zhen Zhang, Mr. Chun Qiu, Dr. Yubin Wang, Dr. Chunhua Liu, Mr. Fuhua Li, Mr. Xianglin Li, and Mr. Feng Yu for their help in the preparation of this book. I want also to express my sincere gratitude to my PhD graduates and postdoctoral fellows, especially Dr. Herman Tsz-Wood Ching, Prof. Ming Cheng, Dr. Ying Fan, Dr. Xiaoyong Zhu, Dr. Wenxiang Zhao, Dr. Shuangxia Niu, Dr. Linni Jian, Dr. Chuang Yu, Dr. Jiangui Li, Dr. Xiaodong Zhang, Dr. Shuang Gao, and Dr. Diyun Wu for their excellent research outcomes, which are essential ingredients of this book.

I am deeply indebted to my colleagues and friends worldwide for their continuous support and encouragement over the years. I also appreciate the reviewers of this book for their thoughtful and constructive comments and the Editors of John Wiley and Sons for their patience and effective support.

Last but not least, I thank my family for the unconditional support and absolute understanding during the writing of this book.

About the Author

K. T. Chau received his B.Sc. (Eng.) degree with First Class Honors, M.Phil., and PhD, all in Electrical and Electronic Engineering from The University of Hong Kong. He joined the alma mater in 1995 and currently serves as Professor in the Department of Electrical and Electronic Engineering, Director of International Research Centre for Electric Vehicles, and Director of B.Eng. degree in Electrical Engineering.

He is Fellow of the Institute of Electrical and Electronics Engineers (IEEE) for Contributions to Energy Systems for Electric and Hybrid Vehicles. He is also a Chartered Engineer, Fellow of the Institution of Engineering and Technology (IET), and Fellow of the Hong Kong Institution of Engineers (HKIE). He has served as editors and editorial board members of various international journals as well as chairs and organizing committee members of many international conferences, especially in the area of Electric Vehicles. He is also an international consultant for electric vehicle technologies.

His teaching and research interests are electric and hybrid vehicles, electric machines, and drives, as well as clean and renewable energies. In these areas, he has published over 400 refereed technical papers, and many industrial reports. His teaching and research philosophy follows the Confucian classic "Li Ji" – Teaching and learning (research) are mutually motivating.

He has received many awards, including the Chang Jiang Chair Professorship; the Environmental Excellence in Transportation Award for Education, Training, and Public Awareness; the Award for Innovative Excellence in Teaching, Learning, and Technology; and the University Teaching Fellow Award.

Contents

1

Introduction

With ever-increasing concern on energy diversification, energy efficiency, and environmental protection, electric vehicles (EVs), including pure electric vehicle (PEV), hybrid electric vehicle (HEV), and fuel-cell electric vehicle (FEV) are becoming attractive for road transportation. Although some of them have become commercially available, there are many challenges and hence opportunities for EV research and development.

In this chapter, the classification of EVs is discussed. Then, an overview of EV challenges is given. Consequently, an overview of various technologies developed for EVs is brought forward.

1.1 What Is an Electric Vehicle?

EVs are nothing new; they were invented 178 years ago but lost the competition for dominance to internal combustion engine vehicles (ICEVs). Actually, the first EV was a battery-powered tricycle built by Thomas Davenport in 1834 (Wakefield, 1994). In 1900, among an annual sale of 4200 automobiles in the US, 38% were EVs, 22% ICEVs, and 40% steam-powered vehicles. At that time, EVs were the preferred road transportation among the wealthy elite. Their cost was equivalent to a Rolls Royce of today. A man with an idea that finished off the EVs for good was Ford. His mass-produced Ford Model T could offer a range double or triple that of the EVs but at only a fraction of their cost. By the 1930s, the EVs almost vanished from the scene. The rekindling of interests in EVs started at the outbreak of the energy crisis and oil shortage in the 1970s. Owing to the growing concern over air quality and the possible consequences of the greenhouse effect in the 1980s, the pace of EV development was accelerated.

In general, EVs are classified as the PEV, HEV, and FEV types on the basis of their energy sources and the propulsion devices (Chan and Chau, 2001; Chau, 2010, 2014). In essence, the PEV is purely fed from electricity, while the propulsion is solely driven by the electric motor; the HEV is sourced from both electricity and gasoline/diesel, while the propulsion involves both the electric motor and engine; and the FEV is directly or indirectly sourced from hydrogen, while the propulsion is solely driven by the electric motor. Moreover, in order to distinguish the refueling means, the HEV can be further categorized into the conventional HEV and the gridable HEV. The conventional one is solely refueled with gasoline/diesel in filling stations, whereas the gridable one can be recharged by electricity via charging ports. On the basis of the hybridization level and the operation feature between the electric motor and engine, the conventional HEV can be further split into the micro HEV, mild HEV, and full HEV. Meanwhile, on the basis of the coordination between the electric motor and engine, the gridable HEV can be further split into the plug-in hybrid electric vehicle (PHEV) and range-extended electric vehicle (REV). This classification is depicted in Figure 1.1.

Electric Vehicle Machines and Drives: Design, Analysis and Application, First Edition. K. T. Chau.

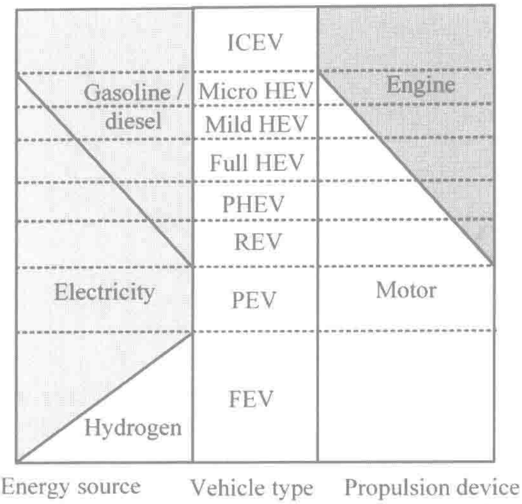


Figure 1.1 Classification of EVs

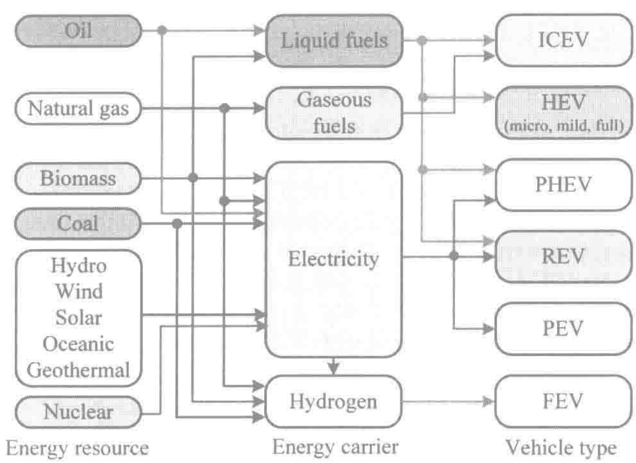


Figure 1.2 Energy diversification of EVs

Deriving from crude oil, the gasoline and diesel are the major liquid fuels for ICEVs. EVs are an excellent solution to rectify this unhealthy dependence because electricity can be generated by almost all kinds of energy resources. Figure 1.2 illustrates the merit of energy diversification due to the use of EVs in which electricity can be produced by thermal power (oil, natural gas, and coal), nuclear power, hydropower, wind power, solar power, oceanic power, geothermal power, and biomass power. In order to compare the overall energy efficiency of EVs with that of ICEVs, their energy conversion processes from crude oil to road load are depicted in Figure 1.3, indicating that EVs are more energy efficient than ICEVs. Moreover, EVs can recover the kinetic energy during braking and utilize it for battery recharging, whereas ICEVs wastefully dissipate this kinetic energy as heat in the brake discs. With this regenerative braking technology, the energy efficiency of EVs can be further boosted by up to 10%.

In many metropolises, ICEVs are responsible for more than 50% of harmful air pollutants and smog-forming compounds. To reduce air pollution from road transportation, the use of EVs is the

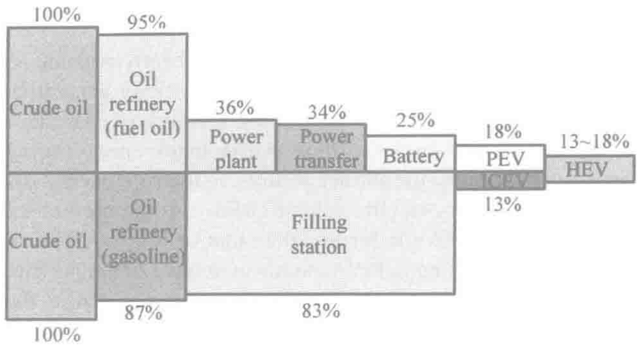


Figure 1.3 Energy efficiency of EVs

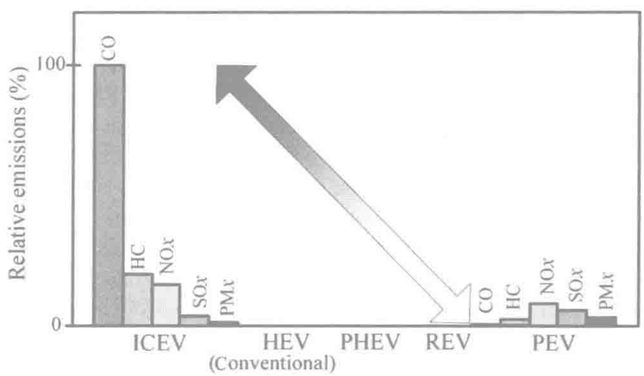


Figure 1.4 Overall harmful emissions of EVs

most viable choice. Definitely, most EVs offer zero roadside emissions. Even taking into account the emissions from refineries to produce gasoline for ICEVs and the emissions from power plants to generate electricity for EVs, the overall harmful emissions of EVs are still much lower than those of ICEVs as indicated in Figure 1.4, where carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matters (PM_x) are taken into account (Chau, 2010). It should be noted that the overall carbon dioxide (CO_2) emission can also be reduced by about 5% with the use of EVs and energy-efficient power plants. This improvement may be further increased when incorporating with higher percentages of clean or renewable power generation, but may even be negative when adopting inefficient coal-fired power plants.

Currently, the conventional HEV has been commercially available and widely accepted as an energy-efficient and environment-friendly vehicle, while the PEV is becoming commercially available and tagged with a zero-emission label. Nevertheless, there are many challenges and opportunities for EV research and development.

1.2 Overview of EV Challenges

There are different types of EVs, including the PEV, conventional HEV, PHEV, REV, and FEV. These EVs can be grouped into the PEV, HEV, gridable HEV, and FEV for discussion, with emphasis on their challenges (Chau, 2012).