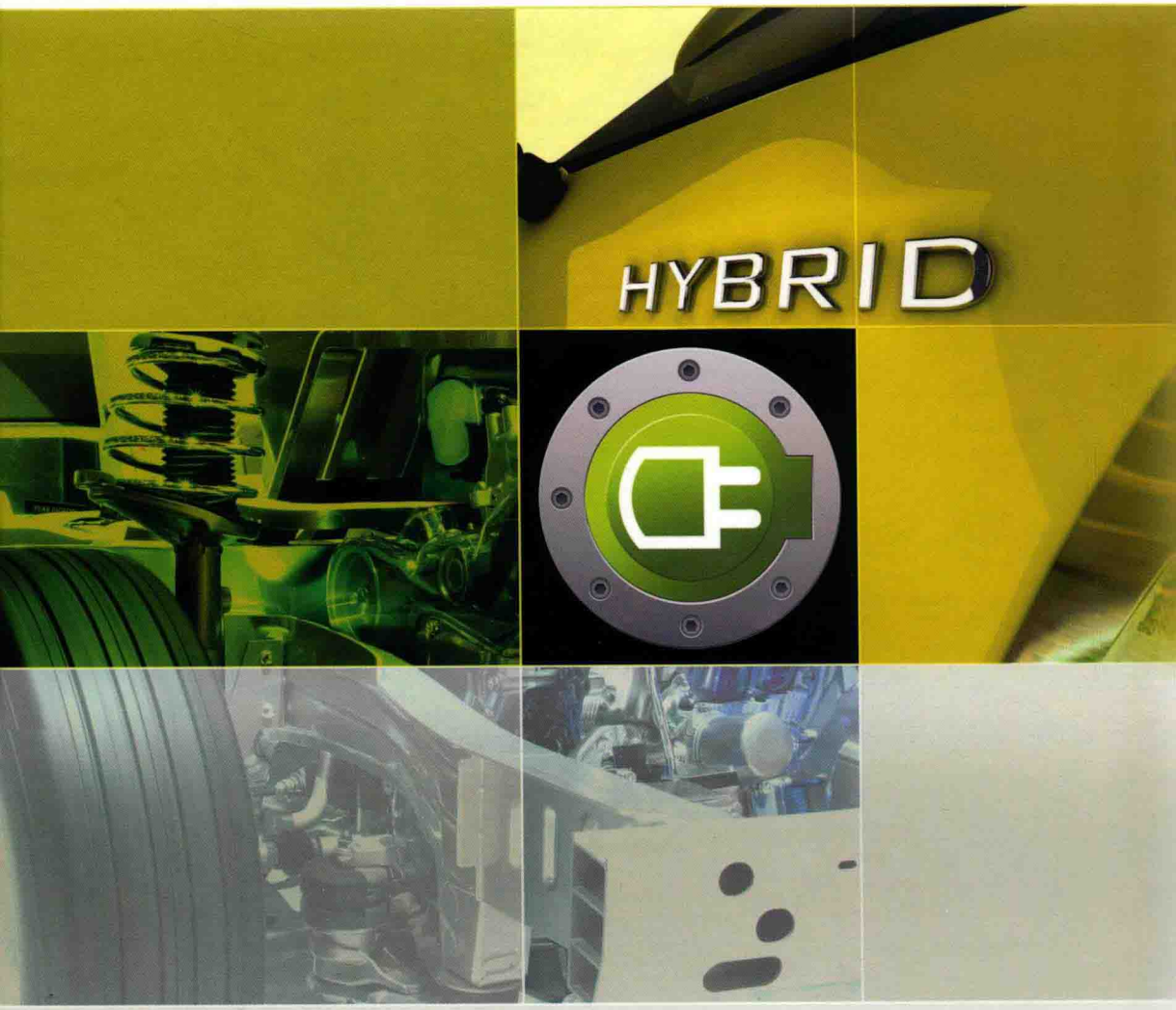
Chris Mi, M. Abul Masrur and David Wenzhong Gao



Hybrid Electric Vehicles

Principles and Applications with Practical Perspectives

WILEY

HYBRID ELECTRIC VEHICLES

PRINCIPLES AND APPLICATIONS WITH PRACTICAL PERSPECTIVES

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Dr. Mi is the recipient of the 2009 Distinguished Research Award of the University of Michigan–Dearborn, the 2007 SAE Environmental Excellence in Transportation (also known as E2T) Award for "Innovative Education and Training Program in Electric, Hybrid and Fuel Cell Vehicles," the 2005 Distinguished Teaching Award of the University of Michigan–Dearborn, the IEEE Region 4 Outstanding Engineer Award, and the IEEE Southeastern Michigan Section Outstanding Professional Award. He is also the recipient of the National Innovation Award (1992) and the Government Special Allowance Award (1994) from the China Central Government. In December 2007, Dr. Mi became a member of the Eta Kappa Nu, the Electrical and Computer Engineering Honor Society, for being "a leader in education and an example of good moral character."

Dr. Mi holds BS and MS degrees from Northwestern Polytechnical University, Xi'an, China, and a PhD from the University of Toronto, Canada. He was the Chief Technical Officer of 1Power Solutions from 2008 to 2010 and worked with General Electric Company from 2000 to 2001. From 1988 to 1994, he was a member of the faculty of Northwestern Polytechnical University, and from 1994 to 1996 he was an Associate Professor and Associate Chair in the Department of Automatic Control Systems, Xi'an Petroleum University, China.

Dr. Mi is the Associate Editor of *IEEE Transactions on Vehicular Technology*, Associate Editor of *IEEE Transactions on Power Electronics – Letters*, associate editor of the *Journal of Circuits, Systems, and Computers* (2007–2009); editorial board member of *International Journal of Electric and Hybrid Vehicles*; editorial board member of *IET Transactions on Electrical Systems in Transportation*; a Guest Editor of *IEEE Transactions on Vehicular Technology, Special Issue on Vehicle Power and Propulsion* (2009–2010), and Guest Editor of *International Journal of Power Electronics, Special Issue on Vehicular Power Electronics and Motor Drives* (2009–2010). He served as the Vice Chair

(2006, 2007) and Chair (2008) of the IEEE Southeastern Michigan Section. He was the General Chair of the Fifth IEEE International Vehicle Power and Propulsion Conference held in Dearborn, MI, September 7–11, 2009. He has also served on the review panel for the National Science Foundation, the US Department of Energy (2006–2010), and the Natural Science and Engineering Research Council of Canada (2010).

Dr. Mi is one of the two Topic Coordinators for the 2011 IEEE International Future Energy Challenge Competition.

M. Abul Masrur received his PhD in electrical engineering from the Texas A & M University, College Station, TX, USA, in 1984. Dr. Masrur is an Adjunct Professor at the University of Detroit Mercy, where he has been teaching courses on Advanced Electric and Hybrid Vehicles, Vehicular Power Systems, Electric Drives and Power Electronics. He was with the Scientific Research Labs., Ford Motor Co., between 1984 and 2001 and was involved in research and development related to electric drives and power electronics, advanced automotive power system architectures, electric active suspension systems for automobiles, electric power assist steering, and standalone UPS protection design, among other things.

Since April 2001, Dr. Masrur has been with the US Army RDECOM-TARDEC (R&D) where he has been involved in vehicular electric power system architecture concept design and development, electric power management, and artificial intelligence-based fault diagnostics in electric drives. He has written over 70 publications, many of which are in public domain international journals and conference proceedings. He also owns eight US patents, two of which are also patented in Europe and one in Japan. He received the Best Automotive Electronics Paper Award from the IEEE Vehicular Technology Society in 1998 for his papers proposing novel vehicular power system architectures in *IEEE Transactions on Vehicular Technology*, and in 2006 was a joint recipient of the SAE Environmental Excellence in Transportation Award – Education, Training, & Public Awareness (or E2T) for a tutorial course he had been jointly presenting on hybrid vehicles.

Dr. Masrur is a Senior Member of the IEEE and from 1999–2007 he served as an Associate Editor (Vehicular Electronics Section) of *IEEE Transactions on Vehicular Technology*. He also served as Chair of the Motor-Subcommittee of the IEEE Power & Energy Society – Electric Machinery Committee for two years ending in December 2010.

David Wenzhong Gao is an Associate Professor of Electrical and Computer Engineering and Director of Renewable Energy and Power Electronics Laboratory at the University of Denver, Denver, CO, USA. Dr. Gao has conducted extensive research in the areas of hybrid electric vehicles, renewable energy, electric power systems, and smart grids, and has published more than 100 papers in international journals and conference proceedings. He presented a tutorial course "Modeling and Simulation Tools for Vehicle Power System" at the US Army Vetronics Institute in Warren, MI, in 2006. In September 2007, he was elected as a member of Sigma Xi. He is a member of Eta Kappa Nu, the Electrical and Computer Engineering Honor Society, and served as a HKN Faculty Advisor. Since June 2003, he has been a Senior Member of the IEEE. He received the Best Paper Award in the Complex Systems Track at the 2002 Hawaii International Conference on System Sciences (HICSS) in January 2002.

Dr. Gao holds a BS degree from Northwestern Polytechnical University, Xi'an, China, an MS degree from Northeastern University, Shenyang, China, and a PhD from Georgia Institute of Technology, Atlanta, USA.

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Preface

It is well recognized today that hybrid electric vehicle (HEV) and electric vehicle (EV) technologies are vital to the overall automotive industry and also to the user, in terms of both better fuel economy and a better effect on the environment. Over the past decade, these technologies have taken a significant leap forward. As they have developed, the literature in the public domain has also grown accordingly, in the form of publications in conference proceedings and journals, and also in the form of textbooks and reference books. Why then was the effort made to write this book? The question is legitimate. The authors observed that existing textbooks have topics like drive cycle, fuel economy, and drive technology as their main focus. In addition, the authors felt that the main focus of such textbooks was on regular passenger automobiles. It is against this backdrop that the authors felt a wider look at the technology was necessary. By this, it is meant that HEV technology is one which is applicable not just to regular automobiles, but also to other vehicles such as locomotives, off-road vehicles (construction and mining vehicles), ships, and even to some extent to aircraft. The authors believe that the information probably exists, but not specifically in textbook form where the overall viewpoint is included. In fact, HEV technology is not new – a slightly different variant of it was present many years ago in diesel–electric locomotives. However, the availability of high-power electronics and the development of better materials for motor technology have made it possible to give a real boost to HEV technology during the past decade or so, making it viable for wider applications.

A textbook, unlike a journal paper, has to be reasonably self-contained. Hence the authors decided to review the basics, including power electronics, electric motors, and storage elements like batteries, capacitors, flywheels, and so on. All these are the main constituent elements of HEV technology. Also included is a discussion on the system-level architecture of the vehicles, modeling and simulation methods, transmission and coupling. Drive cycles and their meaning, and optimization of the vehicular power usage strategy (and power management), have also been included. The issue of dividing power between multiple sources lies within the domain of power management. Power management is an extremely important matter in any power system where more than one source of power is used. These sources may be similar or diverse in nature: that is, they could be electrical, mechanical, chemical, and so on; and even if they all could be similar, they might potentially have different characteristics. Optimization involves a decision on resource allocation in such situations. Some of these optimization methods actually exist in and are used by the utility industry, but have lately attracted significant interest in vehicular applications. To make the book relatively complete and more holistic in nature,

the topics of applications to off-road vehicles, locomotive, ships, and aircraft have been included as well. In the recent past, the interface between a vehicle and the utility grid for plug-in capabilities has become important, hence the inclusion of topics on plug-in hybrid and vehicle-to-grid or vehicle-to-vehicle power transfer. Also presented is a discussion on diagnostics and prognostics, the reliability of the HEV from a system-level perspective, electromechanical vibration and noise vibration harshness (NVH), electromagnetic compatibility and electromagnetic interference (EMC/EMI), and overall life cycle issues. These topics are almost non-existent in the textbooks on HEVs known to the authors. In fact some of the topics have not been discussed much in the research literature either, but are all very important issues. The success of a technology is ultimately manifested in the form of user acceptance and is intimately connected with the mass manufacture of the product. It is not sufficient for a technology to be good; unless a technology, particularly the ones meant for ordinary consumers, can be mass produced in a relatively inexpensive manner, it may not have much of an impact on society. This is very much valid for HEVs as well. The book therefore concludes with a chapter on commercialization issues in HEVs.

The authors have significant industrial experience in many of the technical areas covered in the book, as reflected in the material and presentation. They have also been involved in teaching both academic and industrial professional courses in the area of HEV and EV systems and components. The book evolved to some extent from the notes used in these courses. However, significant amounts of extra material have been added, which is not covered in those courses.

It is expected that the book will fill some of the gaps in the existing literature and in the areas of HEV and EV technologies for both regular and off-road vehicles. It will also help the reader to get a better system-level perspective of these.

There are 15 chapters, the writing of which was shared among the three authors. Chris Mi is the main author of Chapter 1, Chapter 4, Chapter 5, Chapter 9, and Chapter 10. M. Abul Masrur is the main author of Chapter 2, Chapter 6, Chapter 7, Chapter 8, Chapter 14, and Chapter 15. David Wenzhong Gao is the main author of Chapter 3, Chapter 11, Chapter 12, and Chapter 13.

Since this is the first edition of the book, the authors very much welcome any input and comments from readers, and will ensure that any corrections or amendments as needed are incorporated into future editions.

The authors are grateful to all those who helped to complete the book. In particular, a large portion of the material presented is the result of many years of work by the authors as well as other members of their research groups at the University of Michigan–Dearborn, Tennessee Technological University, and University of Denver. Thanks are due to the many dedicated staff and graduate students who made enormous contributions and provided supporting material to this book.

The authors also owe debts of gratitude to their families, who gave tremendous support and made sacrifices during the process of writing this book.

Sincere acknowledgment is made to various sources that granted permission to use certain materials or pictures in this book. Acknowledgments are included where those materials appear. The authors used their best efforts to get approval to use those materials which are in the public domain and on open Internet web sites. Sometimes the original sources of the materials (in some web sites in particular) no longer exist or could not be

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