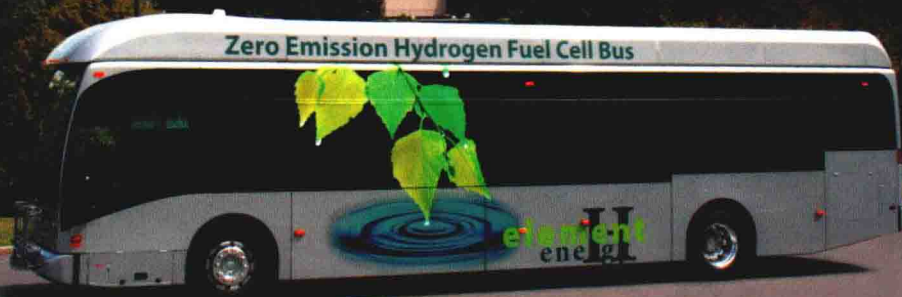


ELECTRIC POWERTRAIN

ENERGY SYSTEMS, POWER ELECTRONICS AND DRIVES
for
HYBRID, ELECTRIC AND FUEL CELL VEHICLES



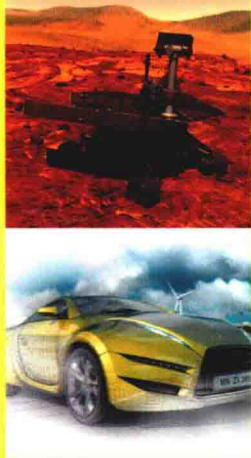
JOHN G. HAYES
G. ABAS GOODARZI

WILEY

Empowers engineering professionals and students with the knowledge and skills required to engineer electric vehicle powertrain architectures, energy storage systems, power electronics converters and electric drives.

The modern electric powertrain is relatively new for the automotive industry, and engineers are challenged with designing affordable, efficient and high-performance electric powertrains as the industry undergoes a technological evolution. Co-authored by two electric vehicle (EV) engineers with decades of experience designing and putting into production all of the powertrain technologies presented, this book provides readers with the hands-on knowledge, skills and expertise they need to rise to that challenge.

This four-part practical guide provides a comprehensive review of battery, hybrid and fuel cell EV systems and the associated energy sources, power electronics, machines, and drives.



- Introduces and holistically integrates the key EV powertrain technologies.
- Provides a comprehensive overview of existing and emerging automotive solutions.
- Provides experience-based expertise for vehicular and powertrain system and sub-system level study, design, and optimization.
- Presents many examples of powertrain technologies from leading manufacturers.
- Discusses the dc traction machines of the Mars rovers, the ultimate EVs from NASA.
- Investigates the environmental motivating factors and impacts of electromobility.
- Presents a structured university teaching stream from introductory undergraduate to postgraduate.
- Includes real-world problems and assignments of use to design engineers, researchers, and students alike.
- Features a **companion website** with numerous references, problems, solutions, and practical assignments.
- Includes introductory material throughout the book for the general scientific reader.
- Contains essential reading for government regulators and policy makers.

Electric Powertrain: Energy Systems, Power Electronics and Drives for Hybrid, Electric and Fuel Cell Vehicles is an important professional resource for practitioners and researchers in the battery, hybrid, and fuel cell EV transportation industry. The resource is a structured, holistic textbook for the teaching of the fundamental theories and applications of energy sources, power electronics, and electric machines and drives to engineering undergraduate and postgraduate students.

John G. Hayes, PhD, MSEE, MBA, lectures at University College Cork, Ireland, and specialises in automotive, industrial and renewable energy systems and related power electronics, machines and electromagnetism. He previously worked in Southern California for ten years at General Motors' Hughes Aircraft subsidiary developing EV propulsion and inductive charging systems for the General Motors EV1, the first modern production EV. John's recent focus has been on the development of integrated and holistic EV teaching materials for the engineering student and the automotive professional.

G. Abas Goodarzi, PhD, P.E., is the Chief Executive Officer and President of US Hybrid Corporation, Torrance, California, which he founded in 1999. He is also the President of US FuelCell, a company formed with the acquisition by US Hybrid of the United Technologies PEM fuel cell transportation division. He served as Senior Scientist at General Motors' Hughes Aircraft subsidiary, and as Technical Director for the General Motors EV1. He has designed various EV, HEV, and FCEV powertrain systems for light, medium, and heavy-duty, on-road, off-road, and special-purpose vehicles.



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POWER TRAIN



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Electric Powertrain

Energy Systems, Power Electronics and Drives for Hybrid,
Electric and Fuel Cell Vehicles

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WILEY

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Electric Powertrain

*To all who have contributed to the electrification of the automobile for a cleaner,
more sustainable future.*

Preface

“The scientific man does not aim at an immediate result. He does not expect that his advanced ideas will be readily taken up. His work is like that of the planter – for the future. His duty is to lay the foundation for those who are to come, and point the way.” Nikola Tesla (1856–1943).

“An inventor is simply a fellow who doesn’t take his education too seriously.” Charles Kettering (1876–1958)

“A problem well stated is a problem half-solved.” Charles Kettering.

This book describes a technological evolution that has major implications around the globe. The objective of this book is to provide the theory behind electric vehicles and insight on the factors motivating the global adoption of these technologies. The story told in the book is largely based on technologies originally developed in Detroit, California, and Japan. However, these technologies are spreading rapidly around the world, having been embraced by German, French, Chinese, and Korean and other global manufacturers. While the car is changing, it is worth noting that the foundations of the modern car are anything but new; vehicular technology and electrical machines are products of the nineteenth century, while semiconductors, lithium-ion batteries, and PEM fuel cells are products of the twentieth century. These technologies are significantly impacting transportation in the early twenty-first century and becoming essential components of the modern vehicle.

I had the privilege of working on the General Motors’ EV1 electric car program in Southern California for ten years. The EV1 was the first electric car developed for mass production in the modern era. I even met my wife, Mary, a mechanical engineer from Detroit, when we worked together on the EV1 – we were both working on the new wireless charging approach known as inductive coupling. I left the automotive world, returning to Ireland to teach, and yet my teaching and research still revolve around automotive topics. The closest connection to automotive history here on the south coast of Ireland is the ancestral home of the Ford family, from which William Ford fled to the United States during the Great Irish Famine in 1847. His son, Henry Ford, was a semi-literate Michigan farm boy, who grew up to revolutionize an industry and create what we now call mass-market consumer capitalism.

While it can be very useful for writing and teaching to be at a distance from the developing story, it is important not to be detached or isolated from such developments. My co-author, Abas Goodarzi, is a former colleague who is living and working to deliver the new technologies. Abas and I started work together at the General Motors' Hughes Aircraft subsidiary in Culver City, California, in October 1990. After directing the development of the EV1 electric powertrain, Abas pursued an electric vehicle start-up. After working in a few more start-ups, Abas founded US Hybrid, where he remains CEO. US Hybrid is a company specializing in delivering battery, hybrid, and fuel cell solutions for heavy-duty transportation. Between us, we have been part of engineering teams which have developed for mass production all of the technologies discussed in this book.

The modern automobile is a great topic for teaching because it is a consumer product to which all students, family, and friends can relate and discuss. Also, it features engineering marvels such as energy storage, combustion engines, electric drives, power electronics, and more. The structure of this book is set up to explain how these technologies interact in the vehicle as a whole and then becomes more technical as the book or a particular chapter unfolds.

The book features problems and assignments of varying technical difficulty for university students. The reader can attempt them based on his or her level.

The car and electrical technology have a history rich with the contributions of many prominent people. Hence, their quotations are often included at the start of a chapter. They generally tie in with the story or underlying philosophies ... and are often fun and thought-provoking.

Acknowledgments

First, we'd like to thank all our colleagues in industry, government, and academia who have provided us feedback, reviews, comments, suggestions, material, and criticism for the book: Mohamed Alamgir, Peter Bardos, Ted Bohn, Amy Bueno, Tim Burress, Kevin Cadogan, Paul Carosa, Gilsu Choi, Amgad Elgowainy, James Francfort, Mark Gibbons, John Goodenough, Oliver Gross, John Hall, Silva Hiti, Gerard Hurley, Joe Kimmel, Tony O'Gorman, Ray Radys, Wally Rippel, James Rohan, Brad Rutledge, Steve Schulz, Matthew Shirk, Charlie Sullivan, and George Woody. Thank you to all the staff at Wiley, especially Michelle Dunckley, Adalfin Jayasingh, Aravind Kannankara and Athira Menon, with a special mention for Peter Mitchell, who answered the question "do you have any textbook which covers all of power electronics and machines and can help me teach an electric vehicle course?" with "No, would you write one?"

A word of thanks to all the supportive staff at University College Cork, especially Michael Egan, and to the former students who have provided help and educated us at times: David Cashman, Kevin Hartnett, Marcin Kacki, Brendan Lyons, Donal Murray, and Marek Rylko; and especially to Brendan Barry, Kevin Davis, Diarmaid Hogan and Robbie Ryan for final proofing and support. A special thank you to the undergraduate and postgraduate students who patiently worked through the various drafts of the book.

We are grateful to the companies and various US agencies for providing us material and would like to acknowledge their great work in the field: AC Propulsion, General Motors, International Council on Clean Transportation (ICCT), Maxon Motors, National Aeronautics and Space Administration (NASA), Jet Propulsion Laboratory (JPL), and the Department of Energy laboratories: Argonne National Laboratory, Oak Ridge National Laboratory, and Idaho National Laboratory.

Abas and I have been lucky to have been supervised in our postgraduate studies by some seminal authors who have led the way in technical education: Ned Mohan of the University of Minnesota, the late John M. D. Murphy of University College Cork, and the late Richard Hoft of the University of Missouri (Columbia).

We wish to acknowledge our former colleagues at Hughes Power Control Systems, and within the General Motors companies and beyond, for their contributions to the EV industry, especially the first commercial battery electric car, featuring the first automotive IGBT traction inverter and an inductive charging infrastructure.

Finally, we thank our extended families and friends for their love, support, and endless patience while we write books or start companies focused on electric vehicles. Mary and Aryan are understanding spouses—Mary is an experienced EV engineer and Aryan is the financial controller at US Hybrid. Thank you to Mary and the girls, Madi, Tasha, and Saoirse, and to Aryan and the boys, Milad and Navid.

Textbook Structure and Suggested Teaching Curriculum

This is primarily an engineering textbook covering the automotive powertrain, energy storage and energy conversion, power electronics, and electrical machines. A significant additional focus is placed on the engineering design, the energy for transportation, and the related environmental impacts. This textbook is an educational tool for practicing engineers and others, such as transportation policy planners and regulators. The modern automobile is used as the vehicle upon which to base the theory and applications, which makes the book a useful educational reference for our industry colleagues, from chemists to engineers. This material is also written to be of interest to the general reader, who may have little or no interest in the power electronics and machines. Introductory science, mathematics, and an inquiring mind suffice for some chapters. The general reader can read the introduction to each of the chapters and move to the next as soon as the material gets too advanced for him or her.

I teach the material across four years here at University College Cork. The material can be taught across various years as outlined in Table I.

The first third of the book (Chapters 1 to 6), plus parts of Chapters 14 and 16, can be taught to the general science or engineering student in the second or third year. It covers the introductory automotive material using basic concepts from mechanical, electrical, environmental, and electrochemical engineering. Chapter 14 on electrical charging and Chapter 16 on electromagnetism can also be used as a general introduction to electrical engineering.

The basics of electromagnetism, ferromagnetism and electromechanical energy conversion (Chapter 16) and dc machines (Chapter 7) are taught to second year (sophomore) engineering students who have completed introductory electrical circuits and physics.

The third year (junior) students typically have covered ac circuit analysis, and so we cover ac machines, such as the induction machine (Chapter 8) and the surface permanent-magnet machine (Chapter 9). As the students typically have studied control theory, we investigate the control of the speed and torque loops of the motor drive (Chapter 15). Power electronics, featuring non-isolated buck and boost converters (Chapter 11), is also introduced in the third year.

The final-year (senior) students then go on to cover the more advanced technologies of the interior-permanent-magnet machine (Chapter 10). Isolated power converters (Chapter 12), such as the full-bridge and resonant converters, inverters (Chapter 13), and power-factor-corrected battery chargers (Chapter 14), are covered

Table I Book content and related teaching.

Chapter	Topic		General	2nd	3rd	4th/PG
1	Vehicles and Energy Sources	Electromobility and the Environment	Y			
2		Vehicle Dynamics	Y			
3		Batteries	Y			
4		Fuel Cells	Y			
5		Conventional and Hybrid Powertrains	Y			
6	Electrical Machines	Introduction to Traction Machines	Y			
7		The Brushed DC Machine		Y		
8		Induction Machines			Y	
9		Surface-Permanent-Magnet AC Machines			Y	
10		Interior-Permanent-Magnet AC Machines				Y
11	Power Electronics	DC-DC Converters			Y	
12		Isolated DC-DC Converters				Y
13		Traction Drives and Three-Phase Inverters				Y
14		Battery Charging				Y
15		Control of the Electric Drive			Y	
16	Basics	Introduction to Electromagnetism, Ferromagnetism, and Electromechanical Energy Conversion		Y		

in the power electronics section. This material can also be covered at the introductory postgraduate level.

Various homework, simulation, and research exercises are presented throughout the textbook. The reader is encouraged to attempt these exercises as part of the learning experience.

About the Companion Web Site

Don't forget to visit the companion web site for this book:

www.wiley.com/go/hayes/electricpowertrain



There you will find valuable material designed to enhance your learning, including:

- 1) Solutions manual
- 2) References
- 3) Slides
- 4) Simulations

Scan this QR code to visit the companion web site:



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