

Chris Mi and M. Abul Masrur

Second Edition



# Hybrid Electric Vehicles

Principles and Applications with Practical Perspectives



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## Hybrid Electric Vehicles

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Principles and Applications  
with Practical Perspectives

Second Edition

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**WILEY**

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## Contents

	<b>About the Authors</b>	<i>xvii</i>
	<b>Preface To the First Edition</b>	<i>xxi</i>
	<b>Preface To the Second Edition</b>	<i>xxv</i>
	<b>Series Preface</b>	<i>xxvii</i>
<b>1</b>	<b>Introduction</b>	<i>1</i>
1.1	Sustainable Transportation	<i>2</i>
1.1.1	Population, Energy, and Transportation	<i>3</i>
1.1.2	Environment	<i>4</i>
1.1.3	Economic Growth	<i>7</i>
1.1.4	New Fuel Economy Requirement	<i>7</i>
1.2	A Brief History of HEVs	<i>7</i>
1.3	Why EVs Emerged and Failed in the 1990s, and What We Can Learn	<i>10</i>
1.4	Architectures of HEVs	<i>11</i>
1.4.1	Series HEVs	<i>12</i>
1.4.2	Parallel HEVs	<i>13</i>
1.4.3	Series–Parallel HEVs	<i>14</i>
1.4.4	Complex HEVs	<i>15</i>
1.4.5	Diesel and other Hybrids	<i>15</i>
1.4.6	Other Approaches to Vehicle Hybridization	<i>16</i>
1.4.7	Hybridization Ratio	<i>16</i>
1.5	Interdisciplinary Nature of HEVs	<i>17</i>
1.6	State of the Art of HEVs	<i>17</i>
1.6.1	Toyota Prius	<i>21</i>
1.6.2	The Honda Civic	<i>21</i>
1.6.3	The Ford Escape	<i>21</i>
1.6.4	The Two-Mode Hybrid	<i>21</i>
1.7	Challenges and Key Technology of HEVs	<i>24</i>
1.8	The Invisible Hand—Government Support	<i>25</i>
1.9	Latest Development in EV and HEV, China’s Surge in EV Sales	<i>27</i>
	References	<i>29</i>
<b>2</b>	<b>Concept of Hybridization of the Automobile</b>	<i>31</i>
2.1	Vehicle Basics	<i>31</i>
2.1.1	Constituents of a Conventional Vehicle	<i>31</i>
2.1.2	Vehicle and Propulsion Load	<i>31</i>

2.1.3	Drive Cycles and Drive Terrain	34
2.2	Basics of the EV	36
2.2.1	Why EV?	36
2.2.2	Constituents of an EV	36
2.2.3	Vehicle and Propulsion Loads	38
2.3	Basics of the HEV	39
2.3.1	Why HEV?	39
2.3.2	Constituents of an HEV	40
2.4	Basics of Plug-In Hybrid Electric Vehicle (PHEV)	40
2.4.1	Why PHEV?	40
2.4.2	Constituents of a PHEV	41
2.4.3	Comparison of HEV and PHEV	42
2.5	Basics of Fuel Cell Vehicles (FCVs)	42
2.5.1	Why FCV?	42
2.5.2	Constituents of a FCV	43
2.5.3	Some Issues Related to Fuel Cells	43
	Reference	43
<b>3</b>	<b>HEV Fundamentals</b>	<b>45</b>
3.1	Introduction	45
3.2	Vehicle Model	46
3.3	Vehicle Performance	49
3.4	EV Powertrain Component Sizing	52
3.5	Series Hybrid Vehicle	55
3.6	Parallel Hybrid Vehicle	60
3.6.1	Electrically Peaking Hybrid Concept	61
3.6.2	ICE Characteristics	66
3.6.3	Gradability Requirement	66
3.6.4	Selection of Gear Ratio from ICE to Wheel	67
3.7	Wheel Slip Dynamics	68
	References	71
<b>4</b>	<b>Advanced HEV Architectures and Dynamics of HEV Powertrain</b>	<b>73</b>
4.1	Principle of Planetary Gears	73
4.2	Toyota Prius and Ford Escape Hybrid Powertrain	76
4.3	GM Two-Mode Hybrid Transmission	80
4.3.1	Operating Principle of the Two-Mode Powertrain	80
4.3.2	Mode 0: Vehicle Launch and Backup	81
4.3.3	Mode 1: Low Range	82
4.3.4	Mode 2: High Range	83
4.3.5	Mode 3: Regenerative Braking	84
4.3.6	Transition between Modes 0, 1, 2, and 3	84
4.4	Dual-Clutch Hybrid Transmissions	87
4.4.1	Conventional DCT Technology	87
4.4.2	Gear Shift Schedule	87
4.4.3	DCT-Based Hybrid Powertrain	88
4.4.4	Operation of DCT-Based Hybrid Powertrain	90

4.4.4.1	Motor-Alone Mode	90
4.4.4.2	Combined Mode	90
4.4.4.3	Engine-Alone Mode	90
4.4.4.4	Regenerative Braking Mode	90
4.4.4.5	Power Split Mode	91
4.4.4.6	Standstill Charge Mode	91
4.4.4.7	Series Hybrid Mode	92
4.5	Hybrid Transmission Proposed by Zhang et al.	92
4.5.1	Motor-Alone Mode	92
4.5.2	Combined Power Mode	93
4.5.3	Engine-Alone Mode	94
4.5.4	Electric CVT Mode	94
4.5.5	Energy Recovery Mode	94
4.5.6	Standstill Mode	94
4.6	Renault IVT Hybrid Transmission	95
4.7	Timken Two-Mode Hybrid Transmission	96
4.7.1	Mode 0: Launch and Reverse	96
4.7.2	Mode 1: Low-Speed Operation	97
4.7.3	Mode 2: High-Speed Operation	97
4.7.4	Mode 4: Series Operating Mode	97
4.7.5	Mode Transition	98
4.8	Tsai's Hybrid Transmission	99
4.9	Hybrid Transmission with Both Speed and Torque Coupling Mechanism	100
4.10	Toyota Highlander and Lexus Hybrid, E-Four-Wheel Drive	102
4.11	CAMRY Hybrid	103
4.12	Chevy Volt Powertrain	104
4.13	Non-Ideal Gears in the Planetary System	106
4.14	Dynamics of the Transmission	107
4.15	Conclusions	108
	References	108
<b>5</b>	<b>Plug-In Hybrid Electric Vehicles</b>	<b>111</b>
5.1	Introduction to PHEVs	111
5.1.1	PHEVs and EREVs	111
5.1.2	Blended PHEVs	112
5.1.3	Why PHEV?	112
5.1.4	Electricity for PHEV Use	114
5.2	PHEV Architectures	115
5.3	Equivalent Electric Range of Blended PHEVs	115
5.4	Fuel Economy of PHEVs	116
5.4.1	Well-to-Wheel Efficiency	116
5.4.2	PHEV Fuel Economy	117
5.4.3	Utility Factor	118
5.5	Power Management of PHEVs	119
5.6	PHEV Design and Component Sizing	121
5.7	Component Sizing of EREVs	122

- 5.8 Component Sizing of Blended PHEVs 123
- 5.9 HEV to PHEV Conversions 123
  - 5.9.1 Replacing the Existing Battery Pack 123
  - 5.9.2 Adding an Extra Battery Pack 125
  - 5.9.3 Converting Conventional Vehicles to PHEVs 126
- 5.10 Other Topics on PHEVs 126
  - 5.10.1 End-of-Life Battery for Electric Power Grid Support 126
  - 5.10.2 Cold Start Emissions Reduction in PHEVs 126
  - 5.10.3 Cold Weather/Hot Weather Performance Enhancement in PHEVs 127
  - 5.10.4 PHEV Maintenance 127
  - 5.10.5 Safety of PHEVs 128
- 5.11 Vehicle-to-Grid Technology 129
  - 5.11.1 PHEV Battery Charging 129
  - 5.11.2 Impact of G2V 131
  - 5.11.3 The Concept of V2G 135
  - 5.11.4 Advantages of V2G 136
  - 5.11.5 Case Studies of V2G 137
- 5.12 Conclusion 140
  - References 140
  
- 6 Special Hybrid Vehicles 143**
  - 6.1 Hydraulic Hybrid Vehicles 143
    - 6.1.1 Regenerative Braking in HHVs 146
  - 6.2 Off-Road HEVs 148
    - 6.2.1 Hybrid Excavators 151
    - 6.2.2 Hybrid Excavator Design Considerations 157
  - 6.3 Diesel HEVs 163
  - 6.4 Electric or Hybrid Ships, Aircraft, and Locomotives 164
    - 6.4.1 Ships 164
    - 6.4.2 Aircraft 167
    - 6.4.3 Locomotives 170
  - 6.5 Other Industrial Utility Application Vehicles 172
    - References 173
    - Further Reading 174
  
- 7 HEV Applications for Military Vehicles 175**
  - 7.1 Why HEVs Can Be Beneficial for Military Applications 175
  - 7.2 Ground Vehicle Applications 176
    - 7.2.1 Architecture – Series, Parallel, Complex 176
    - 7.2.2 Vehicles That Are of Most Benefit 178
  - 7.3 Non-Ground-Vehicle Military Applications 180
    - 7.3.1 Electromagnetic Launchers 181
    - 7.3.2 Hybrid-Powered Ships 182
    - 7.3.3 Aircraft Applications 183
    - 7.3.4 Dismounted Soldier Applications 183

- 7.4 Ruggedness Issues 185
  - References 186
  - Further Reading 187
  
- 8 Diagnostics, Prognostics, Reliability, EMC, and Other Topics Related to HEVs 189**
  - 8.1 Diagnostics and Prognostics in HEVs and EVs 189
    - 8.1.1 Onboard Diagnostics 189
    - 8.1.2 Prognostics Issues 192
  - 8.2 Reliability of HEVs 195
    - 8.2.1 Analyzing the Reliability of HEV Architectures 196
    - 8.2.2 Reliability and Graceful Degradation 199
    - 8.2.3 Software Reliability Issues 201
  - 8.3 Electromagnetic Compatibility (EMC) Issues 203
  - 8.4 Noise Vibration Harshness (NVH), Electromechanical, and Other Issues 205
  - 8.5 End-of-Life Issues 207
    - References 208
    - Further Reading 209
  
- 9 Power Electronics in HEVs 211**
  - 9.1 Introduction 211
  - 9.2 Principles of Power Electronics 212
  - 9.3 Rectifiers Used in HEVs 214
    - 9.3.1 Ideal Rectifier 214
    - 9.3.2 Practical Rectifier 215
    - 9.3.3 Single-Phase Rectifier 216
    - 9.3.4 Voltage Ripple 218
  - 9.4 Buck Converter Used in HEVs 221
    - 9.4.1 Operating Principle 221
    - 9.4.2 Nonlinear Model 222
  - 9.5 Non-Isolated Bidirectional DC–DC Converter 223
    - 9.5.1 Operating Principle 223
    - 9.5.2 Maintaining Constant Torque Range and Power Capability 225
    - 9.5.3 Reducing Current Ripple in the Battery 226
    - 9.5.4 Regenerative Braking 228
  - 9.6 Voltage Source Inverter 229
  - 9.7 Current Source Inverter 229
  - 9.8 Isolated Bidirectional DC–DC Converter 231
    - 9.8.1 Basic Principle and Steady State Operations 231
      - 9.8.1.1 Heavy Load Conditions 232
      - 9.8.1.2 Light Load Condition 234
      - 9.8.1.3 Output Voltage 234
      - 9.8.1.4 Output Power 236
    - 9.8.2 Voltage Ripple 236

9.9	PWM Rectifier in HEVs	242
9.9.1	Rectifier Operation of Inverter	242
9.10	EV and PHEV Battery Chargers	243
9.10.1	Forward/Flyback Converters	244
9.10.2	Half-Bridge DC–DC Converter	245
9.10.3	Full-Bridge DC–DC Converter	245
9.10.4	Power Factor Correction Stage	246
9.10.4.1	Decreasing Impact on the Grid	246
9.10.4.2	Decreasing the Impact on the Switches	247
9.10.5	Bidirectional Battery Chargers	247
9.10.6	Other Charger Topologies	249
9.10.7	Contactless Charging	249
9.10.8	Wireless Charging	250
9.11	Modeling and Simulation of HEV Power Electronics	251
9.11.1	Device-Level Simulation	251
9.11.2	System-Level Model	252
9.12	Emerging Power Electronics Devices	253
9.13	Circuit Packaging	254
9.14	Thermal Management of HEV Power Electronics	254
9.15	Conclusions	257
	References	257
<b>10</b>	<b>Electric Machines and Drives in HEVs</b>	<b>261</b>
10.1	Introduction	261
10.2	Induction Motor Drives	262
10.2.1	Principle of Induction Motors	262
10.2.2	Equivalent Circuit of Induction Motor	265
10.2.3	Speed Control of Induction Machine	267
10.2.4	Variable Frequency, Variable Voltage Control of Induction Motors	269
10.2.5	Efficiency and Losses of Induction Machine	270
10.2.6	Additional Loss in Induction Motors Due to PWM Supply	271
10.2.7	Field-Oriented Control of Induction Machine	278
10.3	Permanent Magnet Motor Drives	287
10.3.1	Basic Configuration of PM Motors	287
10.3.2	Basic Principle and Operation of PM Motors	290
10.3.3	Magnetic Circuit Analysis of IPM Motors	295
10.3.3.1	Unsaturated Motor	300
10.3.3.2	Saturated Motor	301
10.3.3.3	Operation Under Load	303
10.3.3.4	Flux Concentration	303
10.3.4	Sizing of Magnets in PM Motors	304
10.3.4.1	Input Power	306
10.3.4.2	Direct-Axis Armature Reaction Factor	306
10.3.4.3	Magnetic Usage Ratio and Flux Leakage Coefficient	306
10.3.4.4	Maximum Armature Current	307
10.3.4.5	Inner Power Angle	307

10.3.5	Eddy Current Losses in the Magnets of PM Machines	308
10.4	Switched Reluctance Motors	310
10.5	Doubly Salient Permanent Magnet Machines	311
10.6	Design and Sizing of Traction Motors	315
10.6.1	Selection of $A$ and $B$	315
10.6.2	Speed Rating of the Traction Motor	316
10.6.3	Determination of the Inner Power	316
10.7	Thermal Analysis and Modeling of Traction Motors	316
10.7.1	The Thermal Resistance of the Air Gap, $R_{ag}$	317
10.7.2	The Radial Conduction Thermal Resistance of the Rotor Core, $R_{rs}$	318
10.7.3	The Radial Conduction Thermal Resistance of the Poles, $R_{mr}$	319
10.7.4	The Thermal Resistance of the Shaft, $R_{shf}$	319
10.7.5	The Radial Conduction Thermal Resistance of Stator Teeth, $R_{st}$	320
10.7.6	The Radial Conduction Thermal Resistance of the Stator Yoke, $R_{sy}$	320
10.7.7	The Conduction Thermal Resistance between the Windings and Stator, $R_{ws}$	320
10.7.8	Convective Thermal Resistance between Windings External to the Stator and Adjoining Air, $R_{wa}$	321
10.8	Conclusions	323
	References	323
<b>11</b>	<b>Electric Energy Sources and Storage Devices</b>	<b>333</b>
11.1	Introduction	333
11.2	Characterization of Batteries	335
11.2.1	Battery Capacity	335
11.2.2	Energy Stored in a Battery	335
11.2.3	State of Charge in Battery (SOC) and Measurement of SOC	335
11.2.3.1	SOC Determination	336
11.2.3.2	Direct Measurement	336
11.2.3.3	Amp-hr Based Measurement	337
11.2.3.4	Some Better Methods	337
11.2.3.5	Initialization Process	338
11.2.4	Depth of Discharge (DOD) of a Battery	339
11.2.5	Specific Power and Energy Density	339
11.2.6	Ampere-Hour (Charge and Discharge) Efficiency	339
11.2.7	Number of Deep Cycles and Battery Life	340
11.2.8	Some Practical Issues About Batteries and Battery Life	341
11.2.8.1	Acronyms and Definitions	344
11.2.8.2	State of Health Issue in Batteries	348
11.2.8.3	Two-Pulse Load Method to Evaluate State of Health of a Battery	349
11.2.8.4	Battery Management Implementation	352
11.2.8.5	What to Do with All the Above Information	353
11.3	Comparison of Energy Storage Technologies	355
11.3.1	Lead Acid Battery	355
11.3.2	Nickel Metal Hydride Battery	356
11.3.3	Lithium-Ion Battery	356

- 11.4 Ultracapacitors 356
- 11.5 Electric Circuit Model for Batteries and Ultracapacitors 358
  - 11.5.1 Battery Modeling 358
  - 11.5.2 Electric Circuit Models for Ultracapacitors 359
- 11.6 Flywheel Energy Storage System 362
- 11.7 Fuel Cell Based Hybrid Vehicular Systems 364
  - 11.7.1 Introduction to Fuel Cells 364
    - 11.7.1.1 Types of Fuel Cells 364
  - 11.7.2 System Level Applications 364
  - 11.7.3 Fuel Cell Modeling 366
- 11.8 Summary and Discussion 368
  - References 368
  - Further Reading 369
  
- 12 Battery Modeling 371**
  - 12.1 Introduction 371
  - 12.2 Modeling of Nickel Metal Hydride (NiMH) Battery 372
    - 12.2.1 Chemistry of an NiMH Battery 372
  - 12.3 Modeling of Lithium-Ion (Li-Ion) Battery 374
    - 12.3.1 Chemistry in Li-Ion Battery 374
  - 12.4 Parameter Estimation for Battery Models 375
  - 12.5 Example Case of Using Battery Model in an EV System 377
  - 12.6 Summary and Observations on Modeling and Simulation for Batteries 382
    - References 383
    - Further Reading 383
  
- 13 EV and PHEV Battery Charger Design 385**
  - 13.1 Introduction 385
  - 13.2 Main Features of the LLC Resonant Charger 387
    - 13.2.1 Analysis in the Time Domain 387
    - 13.2.2 Operation Modes and Distribution Analysis 389
  - 13.3 Design Considerations for an LLC Converter for a PHEV Battery Charger 393
  - 13.4 Charging Trajectory Design 396
    - 13.4.1 Key Design Parameters 396
    - 13.4.2 Design Constraints 399
  - 13.5 Design Procedures 401
  - 13.6 Experimental Results 401
  - 13.7 Conclusions 407
    - References 407
  
- 14 Modeling and Simulation of Electric and Hybrid Vehicles 409**
  - 14.1 Introduction 409
  - 14.2 Fundamentals of Vehicle System Modeling 410
  - 14.3 HEV Modeling Using ADVISOR 412
  - 14.4 HEV Modeling Using PSAT 416

14.5	Physics-Based Modeling	416
14.5.1	RCF Modeling Technique	417
14.5.2	Hybrid Powertrain Modeling	418
14.5.3	Modeling of a DC Machine	418
14.5.4	Modeling of DC–DC Boost Converter	419
14.5.5	Modeling of Vehicle Dynamics	420
14.5.6	Wheel Slip Model	421
14.6	Bond Graph and Other Modeling Techniques	424
14.6.1	Bond Graph Modeling for HEVs	424
14.6.2	HEV Modeling Using PSIM	425
14.6.3	HEV Modeling Using Simpler and V-Elph	427
14.7	Consideration of Numerical Integration Methods	428
14.8	Conclusion	428
	References	428
<b>15</b>	<b>HEV Component Sizing and Design Optimization</b>	<b>433</b>
15.1	Introduction	433
15.2	Global Optimization Algorithms for HEV Design	434
15.2.1	DIRECT	434
15.2.2	Simulated Annealing	438
15.2.2.1	Algorithm Description	438
15.2.2.2	Tunable Parameters	439
15.2.2.3	Flow Chart	440
15.2.3	Genetic Algorithms	441
15.2.3.1	Flow Chart	441
15.2.3.2	Operators and Selection Method	441
15.2.3.3	Tunable Parameters	443
15.2.4	Particle Swarm Optimization	443
15.2.4.1	Algorithm Description	443
15.2.4.2	Flow Chart	444
15.2.5	Advantages/Disadvantages of Different Optimization Algorithms	444
15.2.5.1	DIRECT	444
15.2.5.2	SA	445
15.2.5.3	GA	445
15.2.5.4	PSO	446
15.3	Model-in-the-Loop Design Optimization Process	446
15.4	Parallel HEV Design Optimization Example	447
15.5	Series HEV Design Optimization Example	452
15.5.1	Control Framework of a Series HEV Powertrain	454
15.5.2	Series HEV Parameter Optimization	454
15.5.3	Optimization Results	456
15.6	Conclusion	459
	References	459
<b>16</b>	<b>Wireless Power Transfer for Electric Vehicle Applications</b>	<b>461</b>
16.1	Introduction	461
16.2	Fundamental Theory	464

- 16.3 Magnetic Coupler Design 468
  - 16.3.1 Coupler for Stationary Charging 469
  - 16.3.2 Coupler for Dynamic Charging 471
- 16.4 Compensation Network 473
- 16.5 Power Electronics Converters and Power Control 475
- 16.6 Methods of Study 477
- 16.7 Additional Discussion 479
  - 16.7.1 Safety Concerns 479
  - 16.7.2 Vehicle to Grid Benefits 481
  - 16.7.3 Wireless Communications 481
  - 16.7.4 Cost 481
- 16.8 A Double-Sided LCC Compensation Topology and its Parameter Design 482
  - 16.8.1 The Double-Sided LCC Compensation Topology 482
  - 16.8.2 Parameter Tuning for Zero Voltage Switching 486
  - 16.8.3 Parameter Design 491
  - 16.8.4 Simulation and Experiment Results 495
    - 16.8.4.1 Simulation Results 495
    - 16.8.4.2 Experimental Results 497
- 16.9 An LCLC Based Wireless Charger Using Capacitive Power Transfer Principle 502
  - 16.9.1 Circuit Topology Design 504
  - 16.9.2 Capacitance Analysis 506
  - 16.9.3 A 2.4kW CPT System Design 506
  - 16.9.4 Experiment 507
- 16.10 Summary 511
  - References 511
  
- 17 Vehicular Power Control Strategy and Energy Management 521**
  - 17.1 A Generic Framework, Definition, and Needs 521
  - 17.2 Methodology to Implement 523
    - 17.2.1 Methodologies for Optimization 528
    - 17.2.2 Cost Function Optimization 531
  - 17.3 Benefits of Energy Management 536
    - References 536
    - Further Reading 537
  
- 18 Commercialization and Standardization of HEV Technology and Future Transportation 539**
  - 18.1 What Is Commercialization and Why Is It Important for HEVs? 539
  - 18.2 Advantages, Disadvantages, and Enablers of Commercialization 539
  - 18.3 Standardization and Commercialization 540
  - 18.4 Commercialization Issues and Effects on Various Types of Vehicles 541
  - 18.5 Commercialization of HEVs for Trucks and Off-Road Applications 542
  - 18.6 Commercialization and Future of HEVs and Transportation 543
    - Further Reading 543

<b>19</b>	<b>A Holistic Perspective on Vehicle Electrification</b>	<b>545</b>
19.1	Vehicle Electrification – What Does it Involve?	545
19.2	To What Extent Should Vehicles Be Electrified?	545
19.3	What Other Industries Are Involved or Affected in Vehicle Electrification?	547
19.4	A More Complete Picture Towards Vehicle Electrification	548
19.5	The Ultimate Issue: To Electrify Vehicles or Not?	551
	Further Reading	553
	<b>Index</b>	<b>555</b>



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His research interests are in electric and hybrid vehicles. He has taught tutorials and seminars on the subject of HEVs/PHEVs for the Society of Automotive Engineers (SAE), the IEEE, workshops sponsored by the National Science Foundation (NSF), and the National Society of Professional Engineers. He has delivered courses to major automotive OEMs and suppliers, including GM, Ford, Chrysler, Honda, Hyundai, Tyco Electronics, A&D Technology, Johnson Controls, Quantum Technology, Delphi, and the European PhD School. He has offered tutorials in many countries, including the USA, China, Korea, Singapore, Italy, France, and Mexico. He has published more than 200 articles and delivered 30 invited talks and keynote speeches. He has also served as a panelist in major IEEE and SAE conferences.

Dr Mi is a recipient of the “Distinguished Teaching Award” and the “Distinguished Research Award” of University of Michigan-Dearborn. He is a recipient of the 2007 IEEE Region 4 “Outstanding Engineer Award,” “IEEE Southeastern Michigan Section Outstanding Professional Award,” and the “SAE Environmental Excellence in Transportation (E2T) Award.” He was also a recipient of the National Innovation Award and the Government Special Allowance Award from the China Central Government. In December 2007, he became a Member of Eta Kappa Nu, which is the Electrical and Computer Engineering Honor Society, for being “a leader in education and an example of good moral character.”

Dr Mi was the chair (2008–2009) and vice-chair (2006–2007) of the IEEE Southeastern Michigan Section, and was the general chair of the 5th IEEE Vehicle Power and Propulsion Conference held in Dearborn, Michigan, USA in September 2009. Dr Mi is one of the three Area Editors of the IEEE Transactions on Vehicular Technology, associate editor of IEEE Transactions on Power Electronics, and Associate Editor of IEEE Transactions on Industry Applications. He served on the review panel for the NSF, the US Department of Energy, the Natural Sciences and Engineering Research Council of

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Dr Mi is also the general co-chair of the IEEE Workshop on Wireless Power Transfer, guest editor-in-chief of the IEEE Journal of Emerging and Selected Topics in Power Electronics – Special Issue on WPT, guest co-editor-in-chief of IEEE Transactions on Power Electronics Special Issue on WPT, guest editor of IEEE Transactions on Industrial Electronics – Special Issue on dynamic wireless power transfer, and steering committee member of the IEEE Transportation Electrification Conference (ITEC, Asian). He is the program chair for the 2014 IEEE International Electric Vehicle Conference (IEVC) in Florence Italy December 2014 and is also the chair for the IEEE Future Direction's Transportation Electrification Initiative (TEI) e-Learning Committee and developed an e-learning module on wireless power transfer.

**M. Abul Masrur** received his PhD in Electrical Engineering from the Texas A & M University, College Station, TX, USA in 1984. Prior to that he received BSc and MSc degrees in Electrical Engineering. He also has a Master's degree in Computer Engineering. Dr Masrur is an Adjunct Professor at the University of Detroit Mercy, where he has been teaching various courses since 2003, which include Advanced Electric and Hybrid Vehicles, Vehicular Power Systems, Electric Drives and Power Electronics. He has also been instructing graduate level courses at the University of Michigan-Dearborn since 2014, related to vehicular electronics and electrical systems. 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, advanced vehicular propulsion, microgrid and vehicle to vehicle (V2V) and vehicle to grid (V2G) systems, wireless power transfer, electric power management, and artificial intelligence-based fault diagnostics in electric drives. He has authored/co-authored over 90 publications, many of which are in public domain international journals and conference proceedings. He is also the co-inventor of eight US patents (and one additional US patent is pending), two of the patents 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 published in the *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 Fellow of the IEEE, cited for “Contributions to fault diagnostics in electric motor drives and automotive electric power systems”. From 1999–2007 he served as an associate editor (Vehicular Electronics Section) of the *IEEE Transactions*

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## Preface To the First Edition

It is well recognized today that, technologies of hybrid electric vehicles (HEVs) and electric vehicles (EVs) 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, which 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 could all 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 they 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, locomotives, ships, and aircraft have also been included. 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 hybrids 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 they 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 between the three authors. Chris Mi is the main author of Chapters 1, 4, 5, 9, and 10. M. Abul Masrur is the main author of Chapters 2, 6, 7, 8, 14, and 15. David Wenzhong Gao is the main author of Chapters 3, 11, 12, and 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 for this book.

The authors also owe a debt 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 that 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 traced. In these cases, the authors have noted where they found the

materials and expressed their acknowledgment. If any of these sources were missed, the authors apologize for that oversight, and will rectify this in future editions of the book if brought to the attention of the publisher. The names of any product or supplier referred to in this book are provided for information only and are not in any way to be construed as an endorsement (or lack thereof) of such product or supplier by the publisher or the authors.

Finally, the authors are extremely grateful to John Wiley & Sons, Ltd and its editorial staff for giving them the opportunity to publish this book and helping in all possible ways. Finally, the authors acknowledge with great appreciation the efforts of the late Ms. Nicky Skinner of John Wiley & Sons, who initiated this book project on behalf of the publisher, but passed away in an untimely way very recently, and so did not see her efforts come to successful fruition.



## Preface To the Second Edition

Although the first edition of this book was very well received by individuals, academic institutions, and others, the authors felt and the publisher also agreed that it would enrich the book and help the readership if we revised some of the materials in the first edition and also added some new items due to the introduction of new technologies in the vehicle electrification technology which has taken place over the past few years. With that in mind, the authors pursued the following activities.

In Chapters 1–11, we revised certain things overall, which included correcting a few relatively minor errors which we noticed. Chapter 6 has been significantly updated with important materials on off-road vehicles, with emphasis on excavators, which are relatively more complex in terms of architecture. Chapter 8 has also been updated to some extent. Chapter 11 on energy storage has been completely reorganized and rewritten to make it more application oriented. Chapter 12 in this edition is a new chapter, with focus on battery modeling. Chapter 13 is also a new chapter, related to battery charger design, which is an important issue in EV and PHEV. Chapters 12 and 13 from first edition have now become chapters 14 and 15, with minor changes incorporated. Chapter 16 is a completely new addition, related to wireless charging. Since wireless power transfer is a new technology and is under serious consideration in the automotive industry for charging of EV and PHEV, the authors felt that it is important to include it in this edition. Previous chapters 14 and 15 from the first edition have now become chapters 17 and 18 with some modifications. Finally, a new Chapter 19 has been added, which takes a holistic perspective on HEV and EV and discusses various viewpoints and pros and cons of introduction of HEV and EV. This chapter also discusses situations where EV and HEV may not necessarily be a good idea, as indicated by various researchers.

This second edition has been written by only the first two authors (Chris Mi and M. Abul Masrur) of the first edition, primarily due to various preoccupations of the third author (David Gao) since writing of the first edition of this book. The authors (Chris Mi and M. Abul Masrur) most sincerely appreciate the contribution of David Gao to the first edition which was very helpful in initiating the undertaking of this book writing project. The authors are also grateful to John Wiley Publishers (UK) who invited us to produce this second edition.

Finally, as is understandable, any text or reference book of this nature may have some inadvertent errors, which could be of typographic, grammatical, or of a technical nature. The authors would be most grateful if readers were to bring those to the notice of the publisher and/or the authors.

*Chris Mi & M. Abul Masrur*



## Series Preface

Hybrid electric vehicles (HEVs) have been in existence for many years. One can see numerous HEVs on the road today, as they are quite commonplace. However, their presence extends well beyond the roads of the world. HEVs are seen on rails, on and beneath our seas, and in the air. The need for ever-increasing efficiency and reduced emissions continues to spur the growth of the HEV market sector as well as ever-improving and complex technologies in support of the expanding demands placed on HEV systems. Thus, the need to fully understand HEVs from an integrated systems perspective is critical for those who design next generation systems, not only in the automotive industry, but across all transportation sectors.

*Modern Hybrid Electric Vehicles* is a second-generation text that presents the hybrid electric vehicle from an integrated systems perspective. It is a well-balanced text that presents a system-level architecture of HEV, that includes design concepts, hardware, and critical aspects of HEV implementation including power usage and management strategies. The text is designed as part of an advanced engineering course in HEV systems and is part of the *Automotive Series* whose primary goal is to publish practical and topical books for researchers and practitioners in industry, and for postgraduates and advanced undergraduates in automotive engineering. The series addresses new and emerging technologies in automotive engineering, supporting the development of more fuel-efficient, safer and more environmentally friendly vehicles. It covers a wide range of topics, including design, manufacture, and operation, and the intention is to provide a source of relevant information that will be of use to leading professionals in the field.

*Modern Hybrid Electric Vehicles* provides a thorough technical foundation for HEV design, analysis, operation, and control. It also, incorporates a number of real-world concepts that are useful to the practicing engineer, resulting in a text that is an excellent blend of analytical concepts and pragmatic applications. The text goes beyond discussions of automobiles and extends the technical discussions to off-road vehicles, locomotives, ships and aircraft, making it an excellent reference for a wide spectrum of transportation systems designers. It also provides thorough insight into HEV system diagnostics, prognostics, and reliability from a traditional mechanical noise vibration harshness (NVH) viewpoint, and it also integrates issues related to electromechanical vibration and to electromagnetic compatibility and electromagnetic interference (EMC/EMI). Such topics are critical in HEV design, and are not typically covered in textbooks. Thus this text provides significantly new insights into HEVs. It is a well-written text,

authored by recognized industrial and academic experts in a field that is critical to the transportation sector providing a thorough understanding of HEV systems from both design and implementation perspectives, and it is a welcome addition to the *Automotive Series*.

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