AUTOMOTIVE SERIES

HYBRID ELECTRIC VEHICLE SYSTEM MODELING AND CONTROL

SECOND EDITION

WEI LIU

WILEY

HYBRID ELECTRIC VEHICLE SYSTEM MODELING AND CONTROL

Automotive Series

Series Editor: Thomas Kurfess

Automotive Aerodynamics	Katz	April 2016
The Global Automotive Industry	Nieuwenhuis and Wells	September 2015
Vehicle Dynamics	Meywerk	May 2015
Vehicle Gearbox Noise and Vibration: Measurement, Signal Analysis, Signal Processing and Noise Reduction Measures	Tůma	April 2014
Modeling and Control of Engines and Drivelines	Eriksson and Nielsen	April 2014
Modelling, Simulation and Control of Two-Wheeled Vehicles	Tanelli, Corno and Savaresi	March 2014
Advanced Composite Materials for Automotive Applications: Structural Integrity and Crashworthiness	Elmarakbi	December 2013
Guide to Load Analysis for Durability in Vehicle Engineering	Johannesson	November 2013

HYBRID ELECTRIC VEHICLE SYSTEM MODELING AND CONTROL

Second Edition

Wei Liu
General Motors, USA

WILEY

To my wife Mei and son Oliver

Contents

Preface **xiv**
List of Abbreviations **xviii**
Nomenclature **xxii**

1 Introduction **1**
1.1 Classification of Hybrid Electric Vehicles 2
1.1.1 Micro Hybrid Electric Vehicles 2
1.1.2 Mild Hybrid Electric Vehicles 2
1.1.3 Full Hybrid Electric Vehicles 3
1.1.4 Electric Vehicles 3
1.1.5 Plug-in Hybrid Electric Vehicles 4
1.2 General Architectures of Hybrid Electric Vehicles 4
1.2.1 Series Hybrid 4
1.2.2 Parallel Hybrid 5
1.2.3 Series–Parallel Hybrid 6
1.3 Typical Layouts of the Parallel Hybrid Electric Propulsion System 7
1.4 Hybrid Electric Vehicle System Components 8
1.5 Hybrid Electric Vehicle System Analysis 10
1.5.1 Power Flow of Hybrid Electric Vehicles 10
1.5.2 Fuel Economy Benefits of Hybrid Electric Vehicles 11
1.5.3 Typical Drive Cycles 11
1.5.4 Vehicle Drivability 11
1.5.5 Hybrid Electric Vehicle Fuel Economy and Emissions 13
1.6 Controls of Hybrid Electric Vehicles 13
References 14

2 Basic Components of Hybrid Electric Vehicles 15
2.1 The Prime Mover 15
2.1.1 Gasoline Engines 15
2.1.2 Diesel Engines 17
2.1.3 Fuel Cells 17
2.2 Electric Motor with a DC–DC Converter and a DC–AC Inverter 20
2.3 Energy Storage System 21
2.3.1 Energy Storage System Requirements for Hybrid Electric Vehicles 21
2.3.2 Basic Types of Battery for Hybrid Electric Vehicle System Applications 25
2.3.3 Ultracapacitors for Hybrid Electric Vehicle System Applications 34
2.4 Transmission System in Hybrid Electric Vehicles 35
References 37

3 Hybrid Electric Vehicle System Modeling 38
3.1 Modeling of an Internal Combustion Engine 38
3.1.1 Cranking (Key Start) 39
3.1.2 Engine Off 41
3.1.3 Idle 41
3.1.4 Engine On 41
3.1.5 Engine Fuel Economy and Emissions 44
3.2 Modeling of an Electric Motor 48
3.2.1 Operation in the Propulsion Mode 48
3.2.2 Operation in the Regenerative Mode 49
3.2.3 Operation in Spinning Mode 49
3.3 Modeling of the Battery System 53
3.3.1 Modeling Electrical Behavior 54
3.3.2 SOC Calculation 56
3.3.3 Modeling Thermal Behavior 56
3.4 Modeling of the Transmission System 59
3.4.1 Modeling of the Clutch and Power Split Device 60
3.4.2 Modeling of the Torque Converter 67
3.4.3 Modeling of the Gearbox 69
3.4.4 Modeling of the Transmission Controller 70
3.5 Modeling of a Multi-mode Electrically Variable Transmission 73
3.5.1 Basics of One-mode ECVT 73
3.5.2 Basics of Two-mode ECVT 78
3.6 Lever Analogy as a Tool for ECVT Kinematic Analysis 85
3.6.1 Lever System Diagram Set-up 85
3.6.2 Lever Analogy Diagram for ECVT Kinematic Analysis 87
3.7 Modeling of the Vehicle Body 91

3.8 Modeling of the Final Drive and Wheel 92
3.8.1 Final Drive Model 92
3.8.2 Wheel Model 92
3.9 PID-based Driver Model 94
3.9.1 Principle of PID Control 95
3.9.2 Driver Model 96
References 96

4 Power Electronics and Electric Motor Drives in Hybrid Electric Vehicles 97
4.1 Basic Power Electronic Devices 97
4.1.1 Diodes 98
4.1.2 Thyristors 99
4.1.3 Bipolar Junction Transistors (BJTs) 101
4.1.4 Metal Oxide Semiconductor Field Effect Transistors (MOSFETs) 103
4.1.5 Insulated Gate Bipolar Transistors (IGBTs) 105
4.2 DC–DC Converters 107
4.2.1 Basic Principle of a DC–DC Converter 107
4.2.2 Step-down (Buck) Converter 109
4.2.3 Step-up (Boost) Converter 117
4.2.4 Step-down/up (Buck-boost) Converter 121
4.2.5 DC–DC Converters Applied in Hybrid Electric Vehicle Systems 125
4.3 DC–AC Inverters 129
4.3.1 Basic Concepts of DC–AC Inverters 129
4.3.2 Single-phase DC–AC Inverters 134
4.3.3 Three-phase DC–AC Inverters 137
4.4 Electric Motor Drives 141
4.4.1 BLDC Motor and Control 141
4.4.2 AC Induction Motor and Control 152
4.5 Plug-in Battery Charger Design 162
4.5.1 Basic Configuration of a PHEV/BEV Battery Charger 162
4.5.2 Power Factor and Correcting Techniques 164
4.5.3 Controls of a Plug-in Charger 168
References 168

5 Energy Storage System Modeling and Control 169
5.1 Introduction 169
5.2 Methods of Determining the State of Charge 171
5.2.1 Current-based SOC Determination Method 172
5.2.2 Voltage-based SOC Determination Method 177
5.2.3 Extended Kalman-filter-based SOC Determination Method 183
5.2.4 SOC Determination Method Based on Transient Response Characteristics (TRCs) 186

5.2.5 Fuzzy-logic-based SOC Determination Method 189
5.2.6 Combination of SOCs Estimated Through Different Approaches 191
5.2.7 Further Discussion on SOC Calculations in Hybrid Electric Vehicle Applications 192
5.3 Estimation of Battery Power Availability 196
5.3.1 PNGV HPPC Power Availability Estimation Method 198
5.3.2 Revised PNGV HPPC Power Availability Estimation Method 199
5.3.3 Power Availability Estimation Based on the Electrical Circuit Equivalent Model 200
5.4 Battery Life Prediction 207
5.4.1 Aging Behavior and Mechanism 207
5.4.2 Definition of the State of Life 209
5.4.3 SOL Determination under Storage Conditions 210
5.4.4 SOL Determination under Cycling Conditions 214
5.4.5 Lithium Metal Plating Issue and Symptoms in Li-ion Batteries 223
5.5 Cell Balancing 224
5.5.1 SOC Balancing 224
5.5.2 Hardware Implementation of Balancing 224
5.5.3 Cell-balancing Control Algorithms and Evaluation 227
5.6 Estimation of Cell Core Temperature 236
5.6.1 Introduction 236
5.6.2 Core Temperature Estimation of an Air-cooled, Cylinder-type HEV Battery 237
5.7 Battery System Efficiency 241
References 242

6 Energy Management Strategies for Hybrid Electric Vehicles 243
6.1 Introduction 243
6.2 Rule-based Energy Management Strategy 244
6.3 Fuzzy-logic-based Energy Management Strategy 245
6.3.1 Fuzzy Logic Control 246
6.3.2 Fuzzy-logic-based HEV Energy Management Strategy 253
6.4 Determination of the Optimal ICE Operational Points of Hybrid Electric Vehicles 261
6.4.1 Mathematical Description of the Problem 261
6.4.2 Procedures of Optimal Operational Point Determination 263
6.4.3 Golden Section Searching Method 264
6.4.4 Finding the Optimal Operational Points 265
6.4.5 Example of the Optimal Determination 265
6.4.6 Performance Evaluation 269
6.5 Cost-function-based Optimal Energy Management Strategy 278
6.5.1 Mathematical Description of Cost-function-based Optimal Energy Management 279
6.5.2 An Example of Optimization Implementation 282

6.6 Optimal Energy Management Strategy Incorporated with Cycle Pattern Recognition 282
6.6.1 Driving Cycle/Style Pattern Recognition Algorithm 282
6.6.2 Determination of the Optimal Energy Distribution 285
References 287

7 Other Hybrid Electric Vehicle Control Problems 288
7.1 Basics of Internal Combustion Engine Control 288
7.1.1 SI Engine Control 288
7.1.2 Diesel Engine Control 289
7.2 Engine Torque Fluctuation Dumping Control Through the Electric Motor 289
7.2.1 Sliding Mode Control 293
7.2.2 Engine Torque Fluctuation Dumping Control Based on the Sliding Mode Control Method 296
7.3 High-voltage Bus Spike Control 298
7.3.1 Bang-Bang Control Strategy of Overvoltage Protection 300
7.3.2 PID-based ON/OFF Control Strategy for Overvoltage Protection 301
7.3.3 Fuzzy-logic-based ON/OFF Control Strategy for Overvoltage Protection 301
7.4 Thermal Control of an HEV Battery System 304
7.4.1 Combined PID Feedback with Feedforward Battery Thermal System Control Strategy 306
7.4.2 Optimal Battery Thermal Control Strategy 308
7.5 HEV/EV Traction Motor Control 311
7.5.1 Traction Torque Control 311
7.5.2 Anti-rollback Control 313
7.6 Active Suspension Control in HEV/EV Systems 313
7.6.1 Suspension System Model of a Quarter Car 314
7.6.2 Active Suspension System Control 318
7.7 Adaptive Charge-sustaining Setpoint and Adaptive Recharge SOC Determination for PHEVs 325
7.7.1 Scenarios of Battery Capacity Decay and Discharge Power Capability Degradation 326
7.7.2 Adaptive Recharge SOC Termination Setpoint Control Strategy 326
7.8 Online Tuning Strategy of the SOC Lower Bound in CS Operational Mode 333
7.8.1 PHEV Charge-sustaining Operational Characteristics 333
7.8.2 PHEV Battery CS-operation SOC Lower Bound Online Tuning 335
7.9 PHEV Battery CS-operation Nominal SOC Setpoint Online Tuning 343
7.9.1 PHEV CS-operation Nominal SOC Setpoint Determination at BOL 343
7.9.2 Online Tuning Strategy of PHEV CS-operation Nominal SOC Setpoint 345
References 347