CONTENTS

Pı	Preface x				
N	omen	clature		xix	
A	bbrev	iations		XXV	
1	Intr	oduction		1	
		General Architectures of Hybrid Electric Vehicle, 2 1.1.1 Series Hybrid, 2 1.1.2 Parallel Hybrid, 3 1.1.3 Series—Parallel Hybrid, 3 Hybrid Vehicle System Components, 5 Hybrid Vehicle System Analysis, 6 1.3.1 Power Flow of Hybrid Vehicles, 6 1.3.2 Typical Drive Cycles, 7 1.3.3 Vehicle Drivability, 8 1.3.4 Vehicle Fuel Economy and Emissions, 8			
2		Controls of Hybrid Vehicle, 8 References, 10		4.4	
2		ic Components of Hybrid Vehicle		11	
	2.1	Prime Mover, 11 2.1.1 Gasoline Engine, 11			

3

4

2.2 2.3	2.1.3 Electric Energy 2.3.1 2.3.2	Diesel Engine, 12 Fuel Cells, 14 Motor with DC/DC Converter and DC/AC Inverter, 15 Storage System, 17 Energy Storage System Requirements for Hybrid Vehicles, 17 Basic Types of Batteries for Hybrid Vehicle System Application, 19 ission System in Hybrid Vehicle, 24	
	Referen	nces, 24	
Hyb	rid Vehi	icle System Modeling	25
3.1 3.2 3.3 3.4	Modeli Modeli 3.4.1 3.4.2	ng of Internal Combustion Engine, 25 ng of Electric Motor, 32 ng of Battery System, 37 ng of Transmission System, 42 Modeling of Clutch and Power Split Device, 42 Modeling of Torque Converter, 50 Modeling of Gear Box, 52	
3.5	3.4.4	Modeling of Geal Box, 32 Modeling of Transmission Controller, 53 ing of Final Drive and Wheel, 56	
3.6 3.7	Modeli PID-Ba	ing of Vehicle Body, 58 ased Driver Model, 59 nces, 61	
Pow	er Elect	tronics and Electric Motor Drives of Hybrid Vehicle	63
4.1	Basic I	Power Electronic Devices, 63 Diodes, 64	
4.2	4.1.2 4.1.3 4.1.4 4.1.5 DC/DC	Thyristors, 65 Bipolar Junction Transistors, 67 Metal-Oxide-Semiconductor Field Effect Transistors, 69 Insulated Gate Bipolar Transistors, 71 C Converter, 72 Basic Principle of DC-DC Converter, 72	
	4.2.2	Step-Down (Buck) Converter, 74 4.2.2.1 Steady-State Operation, 76 4.2.2.2 Output Voltage Ripple, 80	
	4.2.3 4.2.4	Step-Up (Boost) Converter, 83 Step-Down/Up (Buck–Boost) Converter, 86	
	4.2.4	DC-DC Converters Applied in Hybrid Vehicle Systems, 90 4.2.5.1 Isolated Buck DC-DC Converter, 90	
		4.2.5.2 Four-Quadrant DC-DC Converter, 94	

4.3	DC-A	C Inverter, 94	
	4.3.1	Basic Concepts of DC-AC Inverters, 95	
		Single-Phase DC-AC Inverter, 99	
		Three-Phase DC-AC Inverter, 102	
4.4		ic Motor Drives, 106	
	4.4.1	BLDC Motor and Control, 106	
		4.4.1.1 Operation of BLDC Motor, 106	
		4.4.1.2 Torque and Rotating Field Production, 107	
		4.4.1.3 BLDC Motor Control, 108	
		4.4.1.4 BLDC Motor Torque—Speed Characteristics	
		and Typical Technical Parameters, 113	
		4.4.1.5 Sensorless BLDC Motor Control, 113	
	4.4.2		
		4.4.2.1 Basic Principle of AC Induction Motor	
		Operation, 115	
		4.4.2.2 Controls of AC Induction Motor, 118	
4.5	Plug-1	in Battery Charger Design, 124	
		Basic Configuration of PHEV/BEV Battery Charger, 124 Power Factor and Correcting Techniques, 125	
		_	
		Controls of Plug-In Charger, 127 ences, 129	
	Reiere	ences, 129	
Ene	ray Sta	orage System Modeling and Control	131
	-		
5.1			
5.2 Methods of Determining State of Charge, 133			
		Current-Based SOC Determination, 133	
	5,2.2	Voltage-Based SOC Determination, 136 Extended Kalman Filter-Based SOC Determination, 145	
		SOC Determination Based on Transient Response	
	5.2.4	Characteristics, 147	
	525	Fuzzy Logic—Based SOC Determination, 149	
		Combination of Estimated SOCs by Different	
	5.2.0	Approaches, 151	
	5.2.7		
	5.2.7	Vehicle Applications, 152	
5.3	Estim	ation of Battery Power Availability, 154	
	5.3.1	PNGV HPPC Power Availability Estimation, 156	
	5.3.2		
	5.3.3		
		Equivalent Model, 159	
E A		1	
5.4	Batte	ry Life Prediction, 165	
5.4	5.4.1	ry Life Prediction, 165	

6

199

	5.4.3	
	5.4.4	SOL Determination under Cycling Condition, 172
		5.4.4.1 Offline Lifetime Determination under Cycling
		Condition, 173
		5.4.4.2 Online SOL Determination under Cycling
		Condition, 173
5.5	Cell I	Balancing, 180
	5.5.1	SOC Balancing, 181 Hardware Implementation of Balancing, 181
	5.5.2	Hardware Implementation of Balancing, 181
	3.3.3	Cell Balancing Control Algorithms and Evaluation, 184
5.6	Esum	ation of Cell Core Temperature, 192
	5.6.1	Introduction, 192
	5.6.2	Core Temperature Estimation of Air-Cooled
		Cylinder-Type HEV Battery, 193
5.7		y System Efficiency, 196
	Refere	ences, 197
_		
Ene	ergy Ma	magement Strategies of Hybrid Vehicle
6.1	Introd	uction, 199
6.2		Based Energy Management Strategy, 200
6.3	Fuzzy	Logic-Based Energy Management Strategy, 201
	6.3.1	Fuzzy Logic Control, 202
	6.3.2	Fuzzy Logic-Based HEV Energy Management
		Strategy, 209
6.4	Detern	nination of Optimal ICE Operating Points of Hybrid
	Vehicle	e, 218
	6.4.1	Mathematical Description of Problem, 219
	6.4.2	Procedures Determining Optimal Operating Points, 220
	6.4.3	Golden Section Search Method, 221
	6.4.4	Determining Optimal Operating Points, 221
	6.4.5	Example of Optimal Determination, 222
	6.4.6	Performance Evaluation, 226
6.5	Cost F	unction-Based Optimal Energy Management Strategy, 233
	6.5.1	Mathematical Description of Cost Function—Based Optimal
		Energy Management, 234
	6.5.2	Example of Optimization Implementation, 237
6.6	Optima	I Energy Management Strategy Incorporated with Cycle
	Pattern	Recognition, 239
	6.6.1	Driving Cycle/Style Pattern Recognition Algorithm, 239
	6.6.2	Determination of Optimal Energy Distribution, 240
	Referen	nces, 242

7	Othe	er Hybrid Vehicle Control Problems	245
	7.1 7.2	Basics of Internal Combustion Engine Control, 245 Engine Torque Fluctuation Dumping Control Through Electric Motor, 247 7.2.1 Sliding-Mode Control, 248	
		7.2.2 Engine Torque Fluctuation Dumping Control Based on Sliding-Mode Control Method, 251	
	7.3	High-Voltage Bus Spike Control, 253	
	7.4	Thermal Control of HEV Battery System, 258 7.4.1 Combined PID Feedback with Feedforward Battery Thermal System Control Strategy, 260 7.4.2 Optimal Battery Thermal Control Strategy, 262	
	7.5	HEV/EV Traction Motor Control, 265	
	7.0	7.5.1 Traction Torque Control, 265	
		7.5.2 Anti-Rollback Control, 266	
	7.6	Active Suspension Control of HEV/EV Systems, 267 7.6.1 Suspension System Model of a Quarter Car, 269 7.6.2 Active Suspension System Control, 270	
		References, 277	
8		g-In Charging Characteristics, Algorithm, and Impact Power Distribution System	279
	8.1 8.2	Introduction, 279 Plug-in Hybrid Vehicle Battery System and Charging Characteristics, 280 8.2.1 AC-120 Plug-In Charging Characteristics, 280 8.2.2 AC-240 Plug-In Charging Characteristics, 281 8.2.3 Characteristics of Rapid Public Charging, 284	
	8.3	Impacts of Plug-in Charging on Electricity Network, 284 8.3.1 Impact on Distribution System, 286 8.3.2 Impact on Electric Grid, 288	
	8.4	Optimal Plug-In Charging Strategy, 289 8.4.1 Optimal Plug-In Charge-Back Point Determination, 290 8.4.2 Cost-Based Optimal Plug-In Charging Strategy, 291 References, 298	
9	Hyl	brid Vehicle Design and Performance Analysis	299
	9.1 9.2 9.3	31	
		9.3.1 Drivability Calculation, 307	

	9.3.2 Preliminary Sizing of Main Components of Hybrid Vehicle, 310 9.3.2.1 Sizing Prime Mover, 310	
	9.3.2.2 Sizing Transmission/Gear Ratio, 312	
	9.3.2.3 Sizing Energy Storage System, 312	
	9.3.2.4 Design Examples, 315	
9.4	Fuel Economy and Emissions Simulation Calculations, 320 References, 323	
Append		325
	Estimation Techniques	323
A. 1	Dynamic Systems and Mathematical Models, 325	
	A.1.1 Types of Mathematical Models, 325	
	A.1.2 Linear Time-Continuous Systems, 326	
	A.1.2.1 Input—Output Model of Linear Time-Invariant	
	and Time-Continuous System, 326 A.1.2.2 State Space Model of Linear Time-Invariant	
	and Time-Continuous System, 328	
	A.1.3 Linear Discrete System and Modeling, 334	
	A.1.4 Linear Time-Invariant Discrete Stochastic Systems, 335	
Α 2	Parameter Estimation of Dynamic Systems, 341	
11.2	A.2.1 Least Squares, 341	
	A.2.2 Statistical Property of Least-Squares Estimator, 342	
	A.2.3 Recursive Least-Squares Estimator, 344	
	A.2.4 Least-Squares Estimator for Slow Time-Varying	
	Parameters, 347	
	A.2.5 Generalized Least-Squares Estimator, 348	
A.3	State Estimation of Dynamic Systems, 349	
A.4	Joint State and Parameter Estimation of Dynamic Systems, 351	
	A.4.1 Extended Kalman Filter, 351	
	A.4.2 Singular Pencil Model, 353	
A.5	Enhancement of Numerical Stability of Parameter and State	
	Estimation, 356 A.5.1 Square-Root Algorithm, 357	
	A.5.1 Square-Root Algorithm, 357 A.5.2 UDU ^T Covariance Factorization Algorithm, 358	
۸ 6	Modeling and Parameter Identification, 361	
71.0	References, 363	
Append	dix B Advanced Dynamic System Control Techniques	365
B.1	Pole Placement of Control System, 366	
B.2		
	B.2.1 Optimal Control Problem Formulation, 371	
	B.2.2 Pontryagin's Maximum Method, 372	

	B.2.3	Dynamic Programming, 374
	B.2.4	Linear Quadratic Control, 378
B.3	Stocha	stic and Adaptive Control, 381
	B.3.1	Minimum-Variance Prediction and Control, 382
		B.3.1.1 Minimum-Variance Prediction, 382
		B.3.1.2 Minimum-Variance Control, 385
	B.3.2	Self-Tuning Control, 387
	B.3.3	Model Reference Adaptive Control, 389
	B.3.4	Model Predictive Control, 391
B .4	Fault-	Tolerant Control, 392
	B.4.1	Hardware Redundant Control, 394
	B.4.2	Software Redundant Control, 394
	Refere	inces 395

Index 397