

Contents

- 1 Overview of Demand Response 1
 - 1.1 Introduction 1
 - 1.2 History of Demand Responses in North America 2
 - 1.3 Benefits of Demand Responses 3
 - 1.3.1 Peak Load Reduction 4
 - 1.3.2 Congestion Management in Distribution Network 5
 - 1.3.3 Ancillary Service (AS) 6
 - 1.3.4 Emergency Conditions and Prevention of Blackouts 8
 - 1.3.5 Transactive Control with Continuous Response to System Imbalance 9
 - 1.4 Motivations and Barriers for Implementing Demand Responses . . 10
 - 1.5 Demand Response Control 11
 - 1.5.1 Interruptible Loads 12
 - 1.5.2 Direct Load Control (DLC) 12
 - 1.5.3 Time of Use (TOU)/Critical Peak Pricing (CPP)/Critical Peak Rebate (CPR) 13
 - 1.5.4 Real-Time Price (RTP) 13
 - 1.5.5 Controllable Load as Resources (CLR) 14
 - 1.6 Demand Responses in Wholesale Market 14
 - 1.6.1 Overview 15
 - 1.6.2 Demand Responses in North American Markets 18
 - 1.7 Lessons Learned and Outlook 21
 - 1.7.1 Lessons Learned 22
 - 1.7.2 Changes for Future Grid to Enable High DR Participations 23
 - 1.8 Summaries 26
- References 27

2 Modeling Demand Response Resources	29	4.4.2 ERCOT-Dispatched Demand Response	91
2.1 Thermal Characteristics of the TCL	29	4.4.3 Real-Time Energy Market	94
2.2 First-Principle-Based Approach	30	4.5 Load Resources Providing RRS	94
2.3 Measurement-Based Approach	34	4.6 ERCOT Emergency Response Service (ERS)	100
2.3.1 Simplified RCQ Model	35	4.6.1 ERS History and Requirement	100
2.3.2 Linearized ETP Model	37	4.6.2 Capacity Demand Curve	101
2.4 Error Correction by Measurement	38	4.6.3 Baselines for ERS Loads	106
2.5 Parameter Randomization	42	4.7 Load in SCED	109
2.6 Modeling Non-thermostatically Controllable Loads	45	4.7.1 Benefits of Load Participation in the Real-Time Market	110
2.7 Modeling the Base Load	48	4.7.2 Eligibility of Loads in SCED	110
References	50	4.7.3 Modifications to SCED	111
3 Basic Control Approach for Aggregated Demand Response Programs	51	4.7.4 Compensation of Demand Response in the Energy Market	113
3.1 Direct Load Control Algorithms	51	4.7.5 Performance of SCED Dispatch for Load	115
3.1.1 General Design Considerations	51	4.8 Summary	116
3.1.2 Test System Setup	52	Further Reading	119
3.1.3 Test System Initialization	54	5 Integrated Demand Response in the Multi-Energy System	121
3.1.4 Construction of Operation Baseline	54	5.1 Introduction	121
3.1.5 Construction of the Control Signal	55	5.2 Concept of Integrated Demand Response	122
3.1.6 Priority-List-Based HVAC Control Algorithm	56	5.2.1 The Basic Concept of IDR	122
3.1.7 Performance for Providing Load Following Services	62	5.2.2 The Value Analysis of IDR	124
3.2 Indirect Load Control Algorithms	66	5.3 Improve the Economy of Energy Systems	125
3.2.1 Response Curves	66	5.4 Enhance the Reliability of Energy Systems	125
3.2.2 ILC-Based Demand Response under TOU Price	68	5.5 Exploit the Capability of Demand Side Resources	125
3.2.3 ILC-Based Demand Response under the Critical-Peak Price	71	5.5.1 The Techno-Economic Analysis of IDR	126
3.3 Autonomous Load Control Algorithm	73	5.6 IDR Research in the Multi-Energy System	127
3.3.1 Statistics of Raw Frequency Data	74	5.6.1 Modeling	127
3.3.2 Frequency-Responsive Appliance Design Considerations	75	5.6.2 Operation Strategy	129
3.3.3 Triggering Statistics of an ACFR Load	78	5.6.3 Market Behavior	130
3.4 Summary	82	5.7 IDR Application in the Multi-Energy System	131
References	83	5.7.1 The USA	132
4 Demand Responses in ERCOT	85	5.7.2 Europe	132
4.1 Introduction	85	5.7.3 China	133
4.2 Overview of ERCOT	86	5.8 Key Issues and Potential Researches of IDR	134
4.3 ERCOT Market Structure	86	5.9 The Precise Modeling of Multi-Energy Consumption	134
4.3.1 Ancillary Services (AS)	87	5.10 The Scheduling Strategy for MESs with IDR Considering the Influences of Different Energy Prices	135
4.3.2 The Day Ahead Energy Market	88	5.11 The Data-Driven Consumption Strategy of IDR	136
4.3.3 The Real-Time Market	88	5.12 The Market Operation and Mechanism Design Considering IDR	136
4.4 Overview of Demand Response Options in ERCOT	88	5.13 Conclusion	137
4.4.1 Non-ERCOT-Dispatched DR	89	References	138
		Future Reading	142

6	Coupon Incentive-Based Demand Response	143
6.1	Introduction	143
6.2	The CIDR Formulation	146
6.2.1	Information Exchange Scheme	146
6.2.2	Timeline of CIDR	147
6.2.3	Choice of Consumer Baselines	148
6.2.4	ISO/RT0	149
6.2.5	LSE	150
6.2.6	Consumer	150
6.2.7	Adjustment of the Coupon Price	151
6.2.8	Comparisons with the PTR/CPP (Critical Peak Pricing)	152
6.3	Critical Assessment of CIDR	153
6.3.1	Consumer Surplus	154
6.3.2	LSE Profit	155
6.3.3	Social Welfare	155
6.3.4	Robustness of the Retail Rate	156
6.3.5	Readiness for Implementation	156
6.3.6	Pros and Cons	157
6.4	Numerical Case Study	158
6.4.1	Scenario Without the Iteration Between LSEs and Consumers	161
6.4.2	Impact of the Consumer Participation Rate	162
6.5	Conclusion	162
	References	163
7	Distributed Real-Time Demand Response	167
7.1	Introduction	167
7.1.1	Motivation	167
7.1.2	Literature Review and Contribution	168
7.2	Real-Time Demand Response Model	169
7.2.1	Objective	170
7.2.2	Constraints	171
7.3	Lagrangian Relaxation Approach	172
7.4	Sensitivity Analysis	173
7.4.1	General Sensitivity Expressions	174
7.4.2	Objective Sensitivity	175
7.4.3	Variable Sensitivity	176
7.5	Lagrangian Multiplier Optimal Selection Approach	177
7.6	Case Studies	180
7.6.1	Utility Functions Analysis	180
7.6.2	Smart Distribution Grid with 10 Consumers	181
7.6.3	Smart Distribution Grid with 100 Consumers	184
7.6.4	Real-World Distribution Grid with 14 Commercial Consumers	186

7.7	Conclusions	187
Appendix		189
	Variable Sensitivity Simplification	189
	Convergence Analysis	190
References		191

8	Load Resources to Provide Primary Frequency Reserve Service	195
8.1	Introduction of Frequency Control	195
8.2	Impact of Renewable Resource over Inertia and Primary Frequency Control	197
8.3	Frequency Response Reserves at ERCOT	198
8.4	Quantification of FRR Requirement	201
8.4.1	Step 1: Selection of Representative Operation Conditions	202
8.4.2	Step 2: Setup of Dynamic Models	203
8.4.3	Step 3: Quantification of Minimum FRR Requirement	203
8.4.4	Step 4: Derivation of Equivalency Ratio for All Cases	204
8.5	Co-optimization of Energy and FRR in Day-ahead Market	206
8.5.1	Day-ahead market co-optimization model	206
8.5.2	Solution of day-ahead market co-optimization	211
8.5.3	Case Studies	213
8.6	Co-optimization of Energy and FRR in Real-time	219
8.6.1	Problem Formulation	220
8.6.2	Pricing Strategy	222
8.6.3	FFR's Market Behaviors	223
8.7	Conclusions	227
References		228
9	Optimal Response of Residential House Load	231
9.1	Introduction	231
9.2	The Formulation of Appliance Commitment Problem	233
9.2.1	Thermal Dynamic Modes of EWH	234
9.2.2	The Parameter Estimation of EWH Thermal Model	235
9.2.3	The Random Hot-Water-Consumption Model	236
9.2.4	The Comfort Constraints	237
9.3	Solving the Appliance Commitment Problem	237
9.4	Case Studies	241
9.4.1	Day-Ahead Energy Price Forecast	241
9.4.2	A State Queueing Model of Water Heater	241

9.4.3	Transactive Control Strategy	242
9.4.4	Appliance Commitment	243
9.5	Future Work	248
9.6	Conclusions	249
	References	249
	Index	253