## Contents

1.	Intro	duction and Overview	1
	1.1	Introduction 1	
	1.2	Trends of Operating Environment 2	
	1.3	Online TSA 4	
	1.4	Need for New Tools 5	
	1.5	Direct Methods: Limitations and Challenges 6	
	1.6	Purposes of This Book 9	
2.	Syste	m Modeling and Stability Problems	14
	2.1	Introduction 14	
	2.2	Power System Stability Problem 15	
	2.3	Model Structures and Parameters 19	
	2.4	Measurement-Based Modeling 21	
	2.5	Power System Stability Problems 23	
	2.6	Approaches for Stability Analysis 25	
	2.7	Concluding Remarks 27	
3.	Lvan	unov Stability and Stability Regions of Nonlinear	
		mical Systems	29
	3.1	Introduction 29	
	3.2	Equilibrium Points and Lyapunov Stability 30	
	3.3	Lyapunov Function Theory 32	
	3.4	Stable and Unstable Manifolds 34	
	3.5	Stability Regions 37	
	3.6	Local Characterizations of Stability Boundary 38	
	3.7	Global Characterization of Stability Boundary 43	
	3.8	Algorithm to Determine the Stability Boundary 45	
	3.9	Conclusion 49	
4.	Quas	si-Stability Regions: Analysis and Characterization	51
	4.1	Introduction 51	
	4.2	Quasi-Stability Region 51	
	4.3	Characterization of Quasi-Stability Regions 56	
	4.4	Conclusions 58	

5. Ener	gy Function Theory and Direct Methods	60
5.1	Introduction 60	
5.2	Energy Functions 61	
5.3	Energy Function Theory 64	
5.4	Estimating Stability Region Using Energy Functions 69	
5.5	Optimal Schemes for Estimating Stability Regions 73	
5.6	Quasi-Stability Region and Energy Function 75	
5.7	Conclusion 78	
	tructing Analytical Energy Functions for Transient lity Models	80
6.1	Introduction 80	
6.2	Energy Functions for Lossless Network-Reduction Models 81	
6.3		2
6.4	Nonexistence of Energy Functions for Lossy Models 89	•••
6.5	Existence of Local Energy Functions 92	
6.6	Concluding Remarks 93	
	truction of Numerical Energy Functions for Lossy sient Stability Models	94
7.1	Introduction 94	
7.2	A Two-Step Procedure 95	
7.3	First Integral-Based Procedure 98	
7.4	Ill-Conditioned Numerical Problems 105	
7.5	Numerical Evaluations of Approximation Schemes 108	
7.6	Multistep Trapezoidal Scheme 110	
7.7	On the Corrected Numerical Energy Functions 116	
7.8	Concluding Remarks 117	
8. Direc	ct Methods for Stability Analysis: An Introduction	119
8.1	Introduction 119	
8.2	A Simple System 120	
8.3	Closest UEP Method 122	
8.4	Controlling UEP Method 123	
8.5	PEBS Method 125	
	Concluding Demonto 126	
8.6	Concluding Remarks 126	
8.6	adation of the Closest UEP Method	129
8.6		129
8.6 <b>9. Foun</b>	dation of the Closest UEP Method	129
8.6 <b>9. Foun</b> 9.1	Introduction 129	129
8.6  9. Foun  9.1  9.2	Introduction 129 A Structure-Preserving Model 129	129

	9.6	Improved Closest UEP Method 136	
	9.7	Robustness of the Closest UEP 140	
	9.8	Numerical Studies 144	
	9.9	Conclusions 146	
10.	Foun	dations of the Potential Energy Boundary Surface Method	148
	10.1	Introduction 148	
	10.2	Procedure of the PEBS Method 149	
	10.3	Original Model and Artificial Model 150	
	10.4	Generalized Gradient Systems 153	
	10.5	A Class of Second-Order Dynamical Systems 157	
	10.6	Relation between the Original Model and the Artificial Model	160
	10.7	Analysis of the PEBS Method 164	
	10.8	Concluding Remarks 175	
11.	Cont	rolling UEP Method: Theory	177
	11.1	Introduction 177	
	11.2	The Controlling UEP 178	
	11.3	Existence and Uniqueness 180	
	11.4	The Controlling UEP Method 181	
	11.5	Analysis of the Controlling UEP Method 183	
	11.6	Numerical Examples 188	
	11.7	Dynamic and Geometric Characterizations 191	
	11.8	Concluding Remarks 193	
12.	Cont	rolling UEP Method: Computations	196
	12.1	Introduction 196	
	12.2	Computational Challenges 197	
	12.3	Constrained Nonlinear Equations for Equilibrium Points 199	
	12.4	Numerical Techniques for Computing Equilibrium Points 201	
	12.5	Convergence Regions of Equilibrium Points 203	
	12.6	Conceptual Methods for Computing the Controlling UEP 205	
	12.7	Numerical Studies 207	
	12.8	Concluding Remarks 212	
13.		ndations of Controlling UEP Methods for	
	Netw	ork-Preserving Transient Stability Models	215
	13.1	Introduction 215	
	13.2	System Models 216	
	13.3	Stability Regions 218	
	13.4	Singular Perturbation Approach 219	
	13.5	Energy Functions for Network-Preserving Models 221	
	13.6	Controlling UEP for DAE Systems 222	

	13.7	Controlling UEP Method for DAE Systems 224	
	13.8	Numerical Studies 226	
	13.9	Concluding Remarks 230	
14.	Netw	ork-Reduction BCU Method and Its Theoretical Foundation	235
	14.1	Introduction 235	
	14.2	Reduced-State System 236	
	14.3	Analytical Results 237	
	14.4	Static and Dynamic Relationships 246	
	14.5	Dynamic Property (D3) 247	
	14.6	A Conceptual Network-Reduction BCU Method 250	
	14.7	Concluding Remarks 251	
15		erical Network-Reduction BCU Method	254
13.			
	15.1	Introduction 254	
	15.2	Computing Exit Points 256	
	15.3	Stability-Boundary-Following Procedure 257	
	15.4	A Safeguard Scheme 262	
	15.5	Illustrative Examples 263	
	15.6	Numerical Illustrations 270	
	15.7	IEEE Test System 274	
	15.8	Concluding Remarks 275	
16.	Netw	ork-Preserving BCU Method and Its Theoretical Foundation	279
	16.1	Introduction 279	
	16.2	Reduced-State Model 280	
	16.3	Static and Dynamic Properties 285	
	16.4	Analytical Results 288	
	16.5	Overall Static and Dynamic Relationships 292	
	16.6	Dynamic Property (D3) 294	
	16.7	Conceptual Network-Preserving BCU Method 295	
	16.8	Concluding Remarks 299	
17.	Num	erical Network-Preserving BCU Method	300
	17.1	Introduction 300	
	17.1	Computational Considerations 304	
	17.2	Numerical Scheme to Detect Exit Points 305	
	17.3	Computing the MGP 307	
	17.5	Computation of Equilibrium Points 308	
	17.5	Numerical Examples 313	
	17.0	Large Test Systems 319	
	17.7	Concluding Remarks 325	
	17.0	CONCINUING NOMBERS 343	

18.		erical Studies of BCU Methods from Stability dary Perspectives	326
	18.1	Introduction 326	
	18.2	Stability Boundary of Network-Reduction Models 328	
	18.3	Network-Preserving Model 334	
	18.4	One Dynamic Property of the Controlling UEP 339	
	18.5	Concluding Remarks 342	
19.	Study	of the Transversality Conditions of the BCU Method	345
	19.1	Introduction 345	
	19.2	A Parametric Study 346	
	19.3	Analytical Investigation of the Boundary Property 351	
	19.4	The Two-Machine Infinite Bus (TMIB) System 354	
	19.5	Numerical Studies 360	
	19.6	Concluding Remarks 362	
20.	The l	BCU-Exit Point Method	365
	20.1	Introduction 365	
	20.2	Boundary Property 365	
	20.3	Computation of the BCU–Exit Point 373	
	20.4	BCU–Exit Point and Critical Energy 376	
	20.5	BCU–Exit Point Method 378	
	20.6	Concluding Remarks 379	
21.	Grou	p Properties of Contingencies in Power Systems	383
	21.1	Introduction 383	
	21.2	Groups of Coherent Contingencies 385	
	21.3	Identification of a Group of Coherent Contingencies 386	
	21.4	Static Group Properties 387	
	21.5	Dynamic Group Properties 395	
	21.6	Concluding Remarks 399	
22.	Grou	p-Based BCU-Exit Method	401
	22.1	Introduction 401	
	22.2	Group-Based Verification Scheme 402	
	22.3	Linear and Nonlinear Relationships 403	
	22.4	Group-Based BCU–Exit Point Method 410	
	22.5	Numerical Studies 412	
	22.6	Concluding Remarks 413	
23.	Grou	p-Based BCU-CUEP Methods	420
	23.1	Introduction 420	

	23.2	Exact Method for Computing the Controlling UEP 421	
	23.3	Group-Based BCU-CUEP Method 423	
	23.4	Numerical Studies 424	
	23.5	Concluding Remarks 428	
24.	Grou	p-Based BCU Method	430
	24.1	Introduction 430	
	24.2	Group-Based BCU Method for Accurate Critical Energy 431	
	24.3		
	24.4	Numerical Studies 438	
	24.5	Concluding Remarks 445	
25.	Persp	pectives and Future Directions	447
	25.1	Current Developments 447	
	25.2	Online Dynamic Contingency Screening 450	
	25.3	Further Improvements 452	
	25.4	Phasor Measurement Unit (PMU)-Assisted Online ATC	
		Determination 453	
	25.5	Emerging Applications 455	
	25.6	Concluding Remarks 457	
Apj	pendix	(	458
	A1.1	Mathematical Preliminaries 458	
	A1.2	Proofs of Theorems in Chapter 9 459	
	A1.3	Proofs of Theorems in Chapter 10 464	
Bib	liogra	<b>phy</b> 472	
Ind	ex	483	