

Power Electronics and Power Systems


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Experiences on Use of State Estimator in Power System Operations

 Springer

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ISSN 2196-3185

ISSN 2196-3193 (electronic)

Power Electronics and Power Systems

ISBN 978-3-031-62866-5

ISBN 978-3-031-62867-2 (eBook)

<https://doi.org/10.1007/978-3-031-62867-2>

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This book is dedicated to

*“the frontline engineers and support
teams—in recognition of the efforts in
keeping the important tools such as
State Estimator in Control Centers up
and running 24×7”*

Foreword

This book on the use of State Estimators (SE) for power system operations is a compilation of their experiences by different groups all around the world in the installation and operation of SE in a variety of control centers. These book chapters are unique and different from the usual journal and conference papers on this subject as these papers are about field experiences rather than research experience with algorithms and their performance. As such, these papers provide a wonderful collection of implementation experiences that will be beneficial to the many others who are in the process of installing and maintaining new SE in new environments. They are also useful to the researchers as they point to the myriads of challenges that occur in the implementation of SE even though this application is now more than 50 years old. Most engineers who are new to SE are surprised to find that the algorithm is less than 10% of the software, and even when the algorithm works perfectly, the practical challenges are in ensuring that the other 90% of the code runs flawlessly.

The quest for the state estimator started in the mid-1960s as soon as the power flow was solvable by the rudimentary computers of those days. Operations engineers wanted an “On-Line Power Flow,” that is, a power flow solution calculated from the real-time measurements at the transmission substations. The objective was to use the on-line power flow as the base case on which to run contingency cases to ensure the operation of the transmission grid within limits after a disturbance. Unfortunately, the operators found that the on-line power flow would not converge to a solution when all the loads and generation measurements were provided. It slowly dawned on them (actually this aha! moment is attributed to Fred Schweppe of MIT) that the noise in the measurements would not allow the power flow algorithm to converge to the node voltages. However, when the solution was posed as an estimation of the voltages that best matches the measurements in a least squares sense, an answer was always obtained. If the number of measurements were then increased to include voltage magnitudes and line flows, the accuracy of the estimate got better.

In the early 1970s, the State Estimator and the least squares algorithm were well defined and the old name of “on-line power flow” was abandoned in favor of the “state estimator.” The first experimental SEs were developed by the power companies—American Electric Power was the first in the United States. By the mid-

1970s, the utilities wanted SE and the control center vendors developed SE as part of their package of network applications that also included contingency analysis and the operator power flow. This package when integrated with the SCADA-AGC of the existing control centers were given the name Energy Management Systems (EMS). The first vendor-developed EMS went into operation in 1978 at the Wisconsin Electric Power Company installed by Control Data Corporation (now a division of Siemens). This name has stuck and control centers for the bulk power grid are still called EMS, whereas the control centers for the distribution level are known as Distribution Management Systems (DMS) which are now including SE as part of their applications.

Throughout the 1980s, the old SCADA-AGC control centers were replaced by EMS, and in the 1990s, when markets were introduced, the SE became even more important for feeding the market system. Every control center vendor created a group of experts who helped the power companies to install the network applications, of which the SE was the most challenging. This “tuning” of the SE for its first installation became an art which was written about and mainly shared through conferences and IEEE Committees in those days. For example, the measurements needed cleaning for better SE solutions while the SE itself could be used to identify the worst measurement errors. Adjusting the weights of the measurements was important not only for the accuracy of the sensors but to also balance the varying levels of observability in the network. Another issue was the representation of the unobservable external model which required the judicious use of approximations. Some of these challenges still persist as pointed out in the chapter on choosing the external network for a recent control center.

Over time, the SE became a standard control center application, but the application itself became broader. As the ISOs and Reliability Coordinators (RCs) formed the hierarchical control centers, each had its own SE that operated within the hierarchy, that is the ISO may get measurements from a dozen transmission owners who would run their own SE while the ISO will run the SE for the whole ISO area. As the measurements went through the tiered control centers, the time skew in the measurements introduced extra errors for the SE.

When large numbers of PMUs were installed more than 10 years ago, suddenly time synchronized measurements were available at a faster rate. They also allowed a linear SE (LSE) algorithm but only for those portions that were observable with PMUs only. The integration of the traditional SE with the newly available LSE remains a difficult challenge today and is covered in several of the chapters.

The newest challenge is the implementation of SE in the distribution system. All DMS vendors include SE among their applications and many have been field tested. The paucity of measurements in the distribution feeders makes observability a major hurdle to the SE solution. Moreover, PMUs are also available for the distribution system, and some field experiments are covered in the book; these distribution PMUs make new control schemes possible, but the need for such fast control of distribution feeders is not yet widespread.

The book covers all of these challenges through the actual implementation experience of many control centers around the world. Each implementation experience is

different and not always comparable, but it is through such exposure of engineering solutions that best practices will emerge. The transforming grid will require better control and management and the state estimator will remain the root application on which the control applications will be dependent. This book provides a valuable and timely service.

Pullman, WA, USA
August 2024

Anjan Bose

Preface

Dr. Tomas Dy-Liacco, who is often referred to as Father of Modern Energy Control Centers, once said that “Control Centers are here to stay”.

As long as control centers are there, the role of the State Estimator (SE) is expected to exist and has been found to be increasingly pivotal.

We felt that it is important to bring together all aspects of the State Estimator for Power System Grid Operations into one book so that professionals and students alike benefit from the experience of others. As power system engineers, we have witnessed firsthand the transformative impact of the state estimator on the efficiency, reliability, and sustainability of power grid operations.

When SE Was in Its Infancy (Early 1980s)

SE was just beginning; large control centers were just attempting to have SE and many issues related to measurements and models were being ironed out. As the control computers were designed for greater interrupting capabilities to handle SCADA functionality, to have faster display update and SCADA data updates, applications such as SE are considered as a heavy burden on the control computer. Operators were hesitant in running the SE as they didn’t want to have the SCADA performance and display response time suffering due to the SE.

Use of SE in Recent Times (Mid-2020s)

If SE fails to run a cycle or fails to provide a valid solution in a control centers, the operations of the utility/regional organization, such as Independent System Operators (ISOs), almost come to standstill. Even if a single run of SE fails to converge, the support team (24 x 7) swings into action. Downtime of SE is often tried to be kept to less than 20 minutes, as it would lead to a NERC (North

American Electric Reliability Corporation) compliance issue. Further, real-time market operations, which optimize generating resources, can potentially stop for the duration until a backup scheme substituting SE solution approach kicks in, though in a degraded level of operation.

Thus, SE has come a long way in its usage and its dependence in control center operations is obvious as illustrated above. Therefore, it is expected that its criticality in Control Centers is only rising. Recently, SE is also being used in the operations of distribution networks. More recently, SE is also being performed using synchrophasor measurements from phasor measurement units (PMU).

The intent of the book is to provide insights of using SE and in supporting the same in control center operations. It also aimed to bring together the experiences of using SE from different parts of the world.

The book begins with a brief history of state estimator followed by theoretical aspects of state estimator for both transmission and distribution networks. Engineering aspects of building an SE and supporting it in a control center were discussed. Details on modeling with respect to choosing of internal/external/boundary portions of the network model were provided. Further, the challenges of first-time implementation of SE in a control center for operational use were also presented. At the end, the experiences of use of SE both at transmission and distribution levels were presented by various utilities and grid operators across the world.

Chapter 1 provides a brief history of state estimation explaining the birth of the SCADA/EMS system, the role of state estimation and security analysis functions and the acceptance of the computerized operation of power systems concept as a framework of interdependent computer applications harmoniously integrated to support power system scheduling and dispatching.

Chapter 2 covers state estimation algorithms for monitoring and controlling the grid including conventional state estimation, the more recent phasor-based hybrid state estimation, formulation of phasor-based linear state estimation, and also touches upon dynamic state estimation.

Chapter 3 provides theoretical fundamentals of the three-phase distribution state estimator in detail with emphasis on robustness aspects for practical implementations, compromised model for practicability of implementation in distribution networks are discussed. The integration aspects are also discussed in turning the algorithm for practical use.

Chapter 4 discusses engineering aspects of state estimation. The two engineering aspects are covered, one on engineering, a product around the core SE algorithm for practical use, and the other on the engineering tasks involved in supporting a state estimator as applicable in control center production environment. The SE discussed in the chapter is a transmission SE used in grid control centers.

Whereas Chap. 5 discusses the engineering aspects of implementation of distribution state estimator, an algorithm tuning into a product for distribution networks use.

Chapter 6 explains BC Hydro's model reduction method and model comparison results. A repeatable model merge process as well as ongoing model maintenance and validation are also discussed in this chapter. When the networks are very large,

it is difficult to model the complete network in detail. Utilities model in detail only their area and model the remaining network with some kind of equivalents. There is a need to have the reduced external model approach to meet real-time requirements for its state estimator and network security assessment tools. This approach requires extensive initial studies to define appropriate boundaries for the external network and ongoing validation to ensure adequate performance in real-time operations. This chapter provides model reduction method, through BC Hydro's experience on external modelling.

Chapter 7 provides information and details on engineering efforts of initial commissioning of SE. Simple and practical approaches of initial tuning of SE are shared. It further describes how State Estimator needs to be tuned during EMS upgrades and changing EMS vendors.

Chapters 8, 9, 10, 11, 12, 13, 14, 15, 16, and 17 explain the user experiences of their SE implementation, features, operational use in control room, support to control room in using SE, etc.

Chapters 8, 9, 10, 11, and 12 cover the experiences in ERCOT in USA, Hydro One in Canada, State grid in China, California ISO in USA, and Entergy in USA.

Chapters 13, 14, 15, 16, and 17 share experiences in BC Hydro in Canada, National Grid in UK, Tokyo Electric in Japan, Australian Energy Market, and Indian Power system.

Chapters 18, 19, and 20 provide implementations of Linear SE in Malaysia (Asia), American Electric Power (USA), and ComEd (USA). While Chaps. 18 and 19 cover transmission-level implementation, Chap. 20 explains LSE implementation and user experience in a distribution-level microgrid.

Chapter 21 provides state estimation implementations in distribution networks with examples in Europe, USA, and Australia.

Our thanks are due to the authors of the chapters, who have shared their years of rich experience, for their kind heart in putting in efforts and willing to share their knowledge to other professionals through this book.

We are very thankful to Dr Savu Crevat Savulescu, who is well-known veteran in power systems, who kindly agreed to provide an introductory chapter on the history of state estimation.

We are very thankful to Prof. Anjan Bose who is a pioneer and well-known "guru" in Energy Management Systems and kindly agreed to write the Foreword to this book.

We sincerely thank our colleagues throughout our career from whom we learnt a lot and helped us to do our best in providing best tools to the operators in control centers. We also would like to thank our teachers who played a very key role in our education and enabled to become good engineers. Raju thanks his wife Dr. Lakshmi Vinnakota and their son Bapi and their daughter Krishna, and NDR thanks his wife Vasudha Chavali and their daughter Sruti Nuthalapati Jain, for their understanding and support in doing their best in their professional life.

This book is dedicated to "the frontline engineers and support teams—in recognition of their efforts in keeping the important tools such as State Estimator in Control Centers up and running 24×7".

This book is intended for professionals and students alike in electrical engineering, power systems, and grid management. It serves as both an introduction to newcomers and a deep dive for seasoned professionals, offering insights into the theoretical underpinnings and the practical challenges in usage and implementation of state estimators. We hope that this effort achieves this objective.

Folsom, CA, USA
Austin, TX, USA

Veera Raju Vinnakota
Sarma (NDR) Nuthalapati

Contents

1	Brief History of State Estimation	1
	Savu C. Savulescu	
1.1	Real-Time Network Analysis and SCADA/EMS	2
1.2	Redundancy and Observability: Computational Load Dilemma	3
1.3	Time Skew: Parameter Estimation	4
1.4	Wide Area Monitoring Systems (WAMS) and State Estimation	5
1.5	Outlook	6
	References	6
2	State Estimation Algorithms	9
	Saikat Chakrabarti, Ankush Sharma, and Suresh Chandra Srivastava	
2.1	Introduction	9
2.2	Need for State Estimation	10
2.3	Functions of a State Estimator	10
2.4	Weighted Least Squares State Estimator	11
2.4.1	Computation of Measurement Uncertainty	11
2.4.2	Formulation of the WLS Estimator	12
2.4.3	Solving the WLS Estimation Problem	14
2.4.4	Steps of the WLS Algorithm	15
2.4.5	Implementation of WLS SE for Power System	16
2.5	Limitations of SCADA-Based State Estimator	18
2.6	Inclusion of PMU Measurements in State Estimation	19
2.7	Hybrid State Estimator	19
2.7.1	Postprocessing HSE	20
2.7.2	Preprocessing HSE	20
2.7.2.1	Method 1: Current Phasor Magnitude and Angle	21
2.7.2.2	Method 2: Real and Imaginary Part of the Current Phasor	24

- 2.7.2.3 Method 3: Pseudo-Voltage Measurements 26
 - 2.7.3 Challenges in Hybrid State Estimation 28
 - 2.8 Linear State Estimator 28
 - 2.8.1 Formulation of the Linear SE 29
 - 2.9 Dynamic State Estimator 30
 - 2.9.1 Forecasting-Aided State Estimator 31
 - 2.9.2 Extended Kalman Filter 32
 - 2.9.2.1 State Prediction 32
 - 2.9.2.2 State Correction 33
 - 2.10 Conclusion 34
 - References 34
- 3 Theoretical Fundamentals of the Three-Phase Distribution State Estimator** 37

Goran Švenda

 - 3.1 Introduction 38
 - 3.2 DSE Problem Settings 40
 - 3.2.1 Basic Terms and Definitions 40
 - 3.2.2 Differences and Possibilities of Today’s Distribution and Transmission Power Grids 43
 - 3.2.3 Differences and Capabilities of Today’s Distribution and Transmission State Estimations 47
 - 3.2.4 Desires, Interests, and Capabilities 49
 - 3.2.5 Problem Setting: Practically Applicable DSE 50
 - 3.3 Basic Terms 52
 - 3.3.1 A Simple Test Network 52
 - 3.3.2 Measurement Area and Voltage Regulation Zone 55
 - 3.3.2.1 Sets of the Branch, Shunt, and Node Indices 55
 - 3.3.2.2 Power and Current Measurement Areas 56
 - 3.3.2.3 Zone of Voltage Regulation 61
 - 3.3.3 Transformer Area and Transferring Transformer Load Model 63
 - 3.4 DSE Model 66
 - 3.4.1 Verification of Power/Current Measurements 67
 - 3.4.2 Verification of Voltage Measurements 69
 - 3.4.3 Load Allocation 70
 - 3.5 Procedure for Solving the DSE Model 72
 - 3.5.1 Triggering 72
 - 3.5.2 Preparation of the DSE Model 74
 - 3.5.3 Data Preparation 75
 - 3.5.4 Solving the DSE Model 77

3.6	Directions of Development and Application of DSE.....	79
3.6.1	Impact of Changes	79
3.6.2	Future Research Hotspots and Developments	81
3.7	Conclusion	82
	Appendix: Verification—DSE Versus TSE in DPG	83
	Numerical Comparison of DSE and TSE Capabilities	83
	Comparison of the Time Efficiency of TSE and DSE.....	86
	References.....	89
4	Engineering Aspects of State Estimation for Real-Time Use	93
	Veera Raju Vinnakota	
4.1	Introduction	93
4.1.1	Chapter Organization	94
4.1.2	High-Level Overview of State Estimator	95
4.2	Transforming a State Estimation Algorithm to a State Estimator Tool for Real-Time Use	99
4.2.1	Addressing Assumptions Made to the SE Algorithm	100
4.2.2	Addressing Real-Time Requirements of Implementation	102
4.2.3	Addressing Resiliency Requirements	104
4.2.4	Summary of List of Modules to Meet Algorithm Assumptions and RT Requirements	105
4.2.5	Complete Solution Logic	107
4.3	Engineering Tasks Supporting SE Tool	110
4.3.1	Power System Network Model.....	110
4.3.2	Power System Measurements	112
4.3.3	Provide a Network Solution: Tuning, Solution Quality, and Performance Support	114
4.3.3.1	SE Solution Tuning Support	114
4.3.3.2	SE Solution Quality Support	118
4.3.3.3	SE Performance Monitoring Support	119
4.3.4	State Estimator Production System Support	119
4.4	Operational Use of State Estimator	120
4.4.1	SE Values on Station One-Line Displays Along-Side SCADA Values	120
4.4.2	Display of SE-Identified Bad Data	120
4.4.3	Island Detection	121
4.4.4	Base Case Violation (or Thermal Rating Exceedance) Monitoring	121
4.4.5	Phase Angle Monitoring.....	121
4.5	Recent Challenges and Scope for Research	122
4.5.1	Violation of Certain Assumptions of SE Algorithm	122

- 4.5.2 Use of State Estimator Beyond Its Intended Scope 122
- 4.5.3 Vulnerability Aspects of Grid from Observability Perspective 123
- Appendix: Table of Acronyms 123
- References 124
- 5 Engineering Aspects of Implementation of Distribution State Estimator 125**
 - Goran Švenda and Sonja Kanjuh
 - 5.1 Introduction 126
 - 5.2 Transformation of the Power System 130
 - 5.2.1 New Consumers and Producers 131
 - 5.2.2 New Stakeholders in the Electricity Market 132
 - 5.2.3 With the Increase in Penetration of DER and EV, New Problems Appear 132
 - 5.2.4 The Expectations and Problems Are Growing 134
 - 5.3 Necessity to Apply DSE to Real-Life 136
 - 5.4 Industrial-Grade Product 140
 - 5.4.1 Integration of DSE into an Industrial-Grade Product 141
 - 5.4.2 System Architecture 144
 - 5.5 Problems of Implementation and Practical Application 147
 - 5.5.1 Telecommunications Infrastructure 148
 - 5.5.2 Protecting Your Data in a Digital Age 150
 - 5.5.3 Integrations 154
 - 5.5.4 System Tuning and Verification 157
 - 5.5.5 Other 159
 - 5.6 Achieved to Date, and in Front of Us 159
 - 5.7 Conclusion 164
 - References 165
- 6 External Modeling for State Estimation and Network Applications at BC Hydro 167**
 - Qing Zhu, Michael (Ziwen) Yao, Djordje Atanackovic, and Margaret Toussaint
 - 6.1 Introduction 167
 - 6.1.1 BCH System 167
 - 6.1.2 Requirements for the EMS Model 168
 - 6.1.2.1 Compliance with North American Electric Reliability Corporation (NERC)/WECC Mandates 168
 - 6.1.2.2 Full Model Versus Reduced Model: Common Methodology Versus Mandated Model 169

6.2	External Model Reduction.....	170
6.2.1	Background	170
6.2.2	Determination of External System Boundary	171
6.2.3	Results	173
6.3	Model Validation.....	173
6.3.1	Introduction	173
6.3.2	Steady-State Power Flow Model Validation	174
6.3.3	Dynamic Time Domain Simulation Validation	176
6.3.4	Frequency Domain Small Signal Validation.....	176
6.4	Process of External Model Update.....	179
6.4.1	Sources of External Models	179
6.4.2	Process of Model Merge.....	180
6.4.3	Maintenance of External Model.....	184
6.5	Summary	184
	References.....	185
7	Some Aspects of Initial Commissioning of State Estimator.....	187
	Kiamran Radjabli	
7.1	Introduction	187
7.2	SE Mathematical Formulation	188
7.3	SE Issues and Tuning Objectives.....	188
7.4	Monitoring SE Tuning Progress.....	190
7.5	SE Tuning Approach.....	191
7.5.1	General Considerations	191
7.5.2	Configuring SE Parameters.....	192
7.5.3	Detecting and Eliminating Significant Issues.....	193
7.5.4	Bad Data Detection and Topology Inconsistencies	193
7.5.5	Verification of Regulation Schedules	195
7.5.6	Telemetry Accuracy Adjustment	196
7.5.7	Detailed Internal Model Verification.....	196
7.5.8	External Model Expansion	197
7.6	Capitalize on Tuning Experience.....	197
7.7	State Estimator and EMS Upgrades.....	199
7.8	State Estimator and Switching EMS Vendor	201
7.9	Conclusion	203
	References.....	204
8	Experiences on Use of State Estimator in ERCOT Operations	205
	Vamsi Madam, Thinesh Devadhas Mohanadhas, Venkata Kanduri, Tim Mortensen, and Sarma (NDR) Nuthalapati	
8.1	Introduction	206
8.2	Data Requirements.....	207
8.3	Modeling of the Power System Components Using NMMS	207
8.3.1	Generators.....	208

- 8.3.1.1 Wind 208
- 8.3.1.2 Solar 208
- 8.3.1.3 ESR: Batteries 208
- 8.3.1.4 Logical Unit 208
- 8.3.1.5 Combined Cycle Plant (CCP) 209
- 8.3.1.6 Combined Cycle Unit 209
- 8.3.1.7 Split Generation Resource
(SGR)/Jointly Owned Units (JOU) 209
- 8.3.1.8 Private Use Network (PUN) Units 209
- 8.3.2 Lines 209
- 8.3.3 Transformers 210
 - 8.3.3.1 Load Tap Changer (LTC) 210
 - 8.3.3.2 Phase Shifter 210
- 8.3.4 Loads 211
- 8.3.5 Series Devices 212
- 8.3.6 Shunts 212
- 8.3.7 SVCs 212
- 8.3.8 DC Ties 212
- 8.4 Ratings of Components 212
- 8.5 Measurement System 214
 - 8.5.1 SCADA System 215
 - 8.5.2 Measurement Data Quality 215
 - 8.5.3 Pseudo Measurements 217
 - 8.5.4 Observability Analysis 218
 - 8.5.5 Loss of Measurements 218
 - 8.5.5.1 Suspicious Quality Handling 218
 - 8.5.5.2 Handling Incorrect Bulk
Measurement Updates 219
 - 8.5.5.3 Measurement Availability
by Owner 219
 - 8.5.6 Handling Data Quality in RTNET 220
 - 8.5.7 Disabling Measurements 221
 - 8.5.8 Coherency Tests 221
 - 8.5.8.1 Analog Coherency Checking 222
 - 8.5.8.2 Topology Consistency Checking 222
- 8.6 State Estimation 223
 - 8.6.1 Solution Convergence 223
 - 8.6.1.1 Voltage Solution Iterations 223
 - 8.6.1.2 Error Processing Iterations 224
 - 8.6.2 Output Processing 225
 - 8.6.2.1 Generator Limit Expansion 225
 - 8.6.2.2 Load Schedule Adaptation 225
- 8.7 Validation of State Estimation Results 227
 - 8.7.1 Residuals 227
 - 8.7.2 Bus MW/MVAR Mismatches 228

8.7.3	Non-Convergence	229
8.8	Performance of State Estimator	229
8.8.1	Factors Affecting SE Solution	230
8.8.2	Tools to Monitor SE Performance	230
8.8.2.1	Branch Status Error	231
8.8.2.2	Injection Status Error	231
8.8.2.3	CB Status Error	231
8.8.2.4	Topology Errors	232
8.8.2.5	Detection and Identification of Parameter Errors Using SE Results	233
8.8.2.6	Detecting and Identifying the Shunt Device Parameter Error via SE Results	234
8.8.2.7	Tracking Residuals	235
8.8.2.8	Validating SE Results After Model Load	236
8.8.2.9	Dashboard to Display Health of State Estimation	237
8.8.2.10	Study Mode State Estimator Analysis	238
8.9	RTNET Study Mode	238
8.10	Use of State Estimation Results	238
8.10.1	RTCA	239
8.10.2	Market Systems	239
8.10.2.1	System Operations Test Environment	239
8.10.2.2	Market Information System	239
8.11	Conclusions	239
	References	240
9	Experiences on Use of State Estimator at Hydro One	241
	Yinhua Guo	
9.1	Introduction	241
9.2	State Estimation Results Verification	242
9.3	Power System Component Model Issues	243
9.3.1	Transformers and Phase Shifters	244
9.3.2	Transmission Circuits	245
9.3.3	Bus Injections	246
9.4	Telemetry Errors	246
9.5	External Equivalent Model	247
9.6	Weighting Factors	248
9.7	Performance Monitoring	249
9.8	Conclusion	250
	References	251

10 Development and Improvement of State Estimation Implementation in State Grid China 253
 Shi Bonian and Pi Junbo

10.1 Introduction 253

10.2 Algorithms for State Estimation Function 255

 10.2.1 The Design Principles of State Estimation Function 255

 10.2.2 Algorithm of the State Estimation for Hybrid AC and DC Power Grid 256

10.3 Assessment of State Estimation Results and Pre-verifying Methods 260

 10.3.1 Quality Assessment of State Estimation Results 260

 10.3.2 Unbalanced Power-Based Pre-verifying Method 261

10.4 Software Implementation of State Estimation 263

 10.4.1 Submodules of the D5000 State Estimation Software 263

 10.4.2 Demonstration of State Estimation Function 265

 10.4.3 Calculation Results and Assessment 266

 10.4.4 Measurement Analysis and Setting 267

10.5 State Estimation Based on Dispatching Cloud Platform 270

10.6 Conclusions and Future Work 273

References 273

11 Implementation and Support of State Estimator in California ISO Electric Grid Operation 275
 Veera Raju Vinnakota, Trevor Ludlow, Sirajul Chowdhury, and Greg Derner

11.1 Introduction 275

 11.1.1 Chapter Organization 275

 11.1.2 California ISO Overview 276

 11.1.2.1 Network Model Size 277

 11.1.3 Overview of State Estimator Implementation at CAISO 277

 11.1.3.1 Critical Roles of SE at CAISO in Real-Time Operations 277

 11.1.3.2 Basic Functionality of SE: Inputs and Outputs 278

 11.1.3.3 Network Model and Solution Approach for the Whole Network 278

 11.1.3.4 SE Solution Outputs for Operational Use and Support-Teams' Use 279

- 11.2 Some Salient Features of State Estimator Implementation 281
 - 11.2.1 Architecture of EMS and EMNA 281
 - 11.2.2 Balancing Areas' Load and Generation for State Estimator Use 283
 - 11.2.3 Solution Approach for Solving the Network of Observable and Unobservable Portions 284
 - 11.2.3.1 Overview of Solution Approach 284
 - 11.2.3.2 Solution Approach of the Observable Portion of the Network 284
 - 11.2.3.3 Solution Approach of Unobservable Portion of the Network 285
 - 11.2.4 Initial Tuning of State Estimator with Vendor Support 285
 - 11.2.5 Negative Load and Negative Generation Calculation Adjustments 286
 - 11.2.6 Auxiliary Load Related Aspects Supporting Downstream Market System Needs 287
 - 11.2.7 State Estimator Solution Quality Framework 287
 - 11.2.7.1 SE Quality Performance Index (PI) Configurator 288
 - 11.2.7.2 Display of SE Quality Performance Indices 289
 - 11.2.7.3 Solution Output Payload Control 289
 - 11.2.8 SE Measurements and Solution Archival: Save Cases and PI Tracking 290
 - 11.2.8.1 Save Cases 290
 - 11.2.8.2 Archival 291
 - 11.2.9 SE Usage in Operator Training Simulator 291
 - 11.2.10 Backup to State Estimator for Critical Downstream Applications 292
 - 11.2.11 State Estimator in Backup Control Center 293
- 11.3 State Estimator Solution Quality Tuning and Support Approach 293
 - 11.3.1 Approach to SE Solution Quality 295
 - 11.3.2 Tuning to Achieve Area Quality Targets 296
 - 11.3.2.1 Reactive Tuning Metrics 296
 - 11.3.2.2 Proactive Tuning Metrics 297
 - 11.3.2.3 Model Promotion-Based Tuning Metrics 299
 - 11.3.3 Real-Time SE Solution Quality-Based Conditional Output 300

- 11.3.4 Real-Time SE Solution Quality Displays 300
 - 11.3.4.1 EMNA-Based Displays 300
 - 11.3.4.2 Elements of SE Solution Quality
Related PI Tracking and Displays 301
- 11.3.5 Offline Tracking of SE Solution Quality
to Identify Proactive Tuning Actions 302
- 11.4 Support Model of State Estimator 302
 - 11.4.1 Application Support 303
 - 11.4.2 Software Functional Enhancements Support 305
 - 11.4.3 Measurement Support 306
 - 11.4.4 Network Model Support 306
 - 11.4.4.1 Model Data Submission
and Import 306
 - 11.4.4.2 Model Data Validation 307
 - 11.4.4.3 Modeling Practices 307
 - 11.4.5 User Support 308
- Appendix: Table of Acronyms 309
- References 310
- 12 Implementation of State Estimator at Entergy 311**
 - Jinbo Li and Dinakar Kaluvagunta
 - 12.1 Entergy Overview 311
 - 12.2 Entergy State Estimation 312
 - 12.2.1 Network Topology Processor 313
 - 12.2.2 Bad Topology Detection 313
 - 12.2.2.1 De-energized Buses
and De-energized Substations 317
 - 12.3 Observability Analysis 318
 - 12.3.1 Observable Bus Rate 318
 - 12.3.2 Area-Based Available Rates 318
 - 12.4 Bus Load Scheduler 320
 - 12.5 State Estimate 320
 - 12.6 Abnormal SE Solutions Diagnosis 321
 - 12.6.1 SE Not Converged 321
 - 12.6.2 SE Mismatched Solutions 322
 - 12.6.3 Estimated Loads with Low Power Flow
Factors 322
 - 12.6.4 Issues Lowering Observability 322
 - 12.7 Database Updates 323
 - 12.8 Pre-DB Checks 323
 - 12.8.1 Extra Data Validations 324
 - 12.8.1.1 Dangling Node/Dead Node
Detection 324
 - 12.8.1.2 Transformer from/to Base KVs
and KV Level Inconsistence 324

12.8.1.3	Unit Cap Curves	325
12.8.1.4	Missing Contingency Element Detection	325
12.8.2	Solution Quality Checks	325
12.9	External Modeling	325
12.10	Conclusions	326
13	BC Hydro’s Experience with State Estimator in Real-Time Operations	327
	Qing Zhu, Djordje Atanackovic, and Margaret Toussaint	
13.1	Overview	327
13.1.1	Overview of BC Hydro Power System	327
13.1.2	Overview of State Estimator Implementation	328
13.2	State Estimator Features Unique to BCH	329
13.2.1	Pseudo-Measurements and Load Allocation Factor	329
13.2.1.1	Overview of Load Injections in SE	329
13.2.1.2	BCH’s Load Allocation Factor Program	329
13.2.1.3	Other Types of Pseudo-Measurements	331
13.2.2	Pre-SE and Post-SE	332
13.2.2.1	SE Flowchart Overview	332
13.2.2.2	Pre-SE	332
13.2.2.3	Post-SE	334
13.2.3	Miscellaneous BCH Customizations	335
13.2.3.1	Enforcing Flat Start	336
13.2.3.2	SE Stall Detection	336
13.2.3.3	SE No Solution Detection	336
13.2.3.4	Auto Rerun upon SE Convergence Failure	336
13.2.3.5	Voltage-Dependent Multiple Unit Capability Curves	337
13.3	SE Quality Measures	337
13.3.1	Performance Indices and Tracking	337
13.3.2	BCH SE Tuning Experience	338
	References	339
14	Use of State Estimation for Power System Grid Operations at the National Grid Electricity System Operator, United Kingdom	341
	Kanwar Dhesei	
14.1	Introduction to NGESO	341
14.2	Introduction to NGESO’s State Estimator	343
14.3	State Estimator Algorithm	344
14.4	Tuning the State Estimator Solution	347

14.5	State Estimator Reliability Monitoring	348
14.6	Challenges with State Estimation for NGESO	349
14.7	Validation Activities	351
14.8	Enhancements to NGESO State Estimator	355
14.9	Conclusions	358
	References	359
15	Use of State Estimator for Grid Operations at TEPCO in Japan	361
	Teruo Ohno, Hidenori Chigira, and Shigeo Kurihara	
15.1	Background	361
15.2	Use of State Estimator	363
15.3	Modeling of the HV System	365
15.4	Modeling of the Neighboring System	366
15.5	Calculation Flow	369
	References	371
16	Experiences in State Estimation at the Australian Energy Market Operator	373
	Stephen Boroczky, Bryan Connell, and Ahmed Radi	
16.1	The Australian Power System Landscape	373
	16.1.1 The National Electricity Market	373
	16.1.2 The South West Interconnected System	375
16.2	The Role of the Australian Energy Market Operator	376
16.3	State Estimation for the Operation of the AEMO Market Dispatch Engines	377
16.4	State Estimation for Situational Awareness	379
16.5	SCADA Requirements for State Estimation	382
16.6	The Energy Management System	383
16.7	State Estimator Description	383
16.8	State Estimator Configuration	385
16.9	Some AEMO Customisations	386
16.10	Network Model	386
16.11	Typical Estimation Issues	387
16.12	Estimation Performance Metrics	388
16.13	Existing and Future Enhancements and Trends	389
16.14	Conclusion	392
	References	392
17	Experiences on Usages of State Estimation in Indian Power System	395
	Mohneesh Rastogi, Harish Kumar Rathour, Debasis De, S. C. Saxena, K. Muralikrishna, R. K. Porwal, and S. R. Narasimhan	
17.1	Introduction	395
17.2	Hierarchical Structure of Control Centers	397
17.3	Integration of SCADA and EMS Applications	398

- 17.4 Power System Network Modelling..... 400
 - 17.4.1 Power System Elements 401
 - 17.4.1.1 Transmission Lines 401
 - 17.4.1.2 Transformers 401
 - 17.4.1.3 Generators..... 402
 - 17.4.1.4 Loads 403
 - 17.4.1.5 Shunts 403
 - 17.4.1.6 Series Devices 404
 - 17.4.1.7 FACTS Devices 404
 - 17.4.1.8 HVDC Elements 404
 - 17.4.2 Type of Power System Network Model..... 406
 - 17.4.2.1 Node-Breaker Model 407
 - 17.4.2.2 Bus-Branch Model..... 407
 - 17.4.3 Network Reduction 407
 - 17.4.3.1 Truncation of Network 409
 - 17.4.3.2 Equivalencing of Network..... 410
- 17.5 Network Model Creation at National Level 412
 - 17.5.1 Structure of Network Model 413
 - 17.5.2 Stitching of Regional Level Network Model 413
 - 17.5.3 Missed Information in Stitched Network Model..... 414
 - 17.5.3.1 Node Connectivity with Power System Elements..... 414
 - 17.5.3.2 Static Parameter Errors 415
 - 17.5.3.3 Interlinking of SCADA and Network Model 415
 - 17.5.4 Validation of Network Model with Offline Database..... 415
- 17.6 Network Topology Processor (NTP)..... 416
- 17.7 State Estimation..... 417
 - 17.7.1 Weighted Least Square Error State Estimation 417
 - 17.7.2 State Estimation Solution Parameters..... 418
 - 17.7.3 Orthogonal Decomposition Algorithm [6]..... 419
 - 17.7.4 Assignment of Weights to the Measurements 422
 - 17.7.5 Performance Monitoring 423
- 17.8 Topology Estimation..... 424
- 17.9 Observability Analysis [7]..... 424
- 17.10 Use of Pseudo-Measurements 425
- 17.11 Execution of State Estimator Application 426
- 17.12 Dependency of SE Solution on Other Applications 427
- 17.13 Tuning of State Estimation 428
 - 17.13.1 Various Issues with Measurements..... 428
 - 17.13.2 Corrections of Modelling Errors 428
 - 17.13.3 Corrections of Telemetry Errors 429
 - 17.13.4 Sign Convention of Values 429

17.13.5	Location of Measurement	430
17.13.6	Reactive Power Measurement Validation	432
17.13.7	Handling Digital Data	432
17.13.7.1	IEC-104 Convention for Status of Switching Devices	433
17.13.7.2	Incorrect Convention of Isolator Status (Table 17.3)	433
17.13.7.3	Incorrect Convention of Circuit Breaker Status	433
17.13.7.4	Isolator Status Point Type Different Between Control Centers	435
17.13.8	State Estimation Solution for Base Case Preparation for Other EMS Applications	435
17.13.8.1	Power Flow Solution	436
17.13.8.2	Real-Time Contingency Analysis (RTCA)	436
17.13.8.3	Short Circuit Analysis	437
17.13.8.4	Optimal Power Flow	437
17.13.8.5	SE Solution Base Case for Dispatcher Training Simulator	438
17.13.8.6	SE Solution Base Case for Dynamic Security Assessment	439
17.14	Errors Impacting Performance of State Estimation	440
17.14.1	Parameter Errors	440
17.14.2	Telemetry Errors	440
17.14.3	Modelling Errors	441
17.14.4	Sampling Errors	442
17.14.5	Communication Delay	443
17.14.6	Identification of Bad Data in Measurements	443
17.14.7	Monitoring of Bad Data	448
17.14.8	Rectification Methodologies	448
17.15	Visualization of Bad Data	450
17.16	Validation of Network Model	450
17.17	Conclusions/Way Forward	451
	References	452
18	Implementation of Linear State Estimator: Tenaga Nasional Berhad (TNB) Malaysia Experience	453
	Mohd Khairun Nizam Mohd Sarmin, Nira Saadun, Muhamad Tarmizi Azmi, Sheikh Kamar Sheikh Abdullah, Nik Sofizan Nik Yusuf, Ahmad Zuhdi Muhamad Zamani, Marianna Vaiman, Michael Vaiman, Mark Povolotskiy, and Mikhail Karpoukhin	
18.1	Background	453

- 18.1.1 Overview of Tenaga Nasional Berhad (TNB) Malaysia 453
- 18.1.2 Purpose of the LSE Platform 455
- 18.2 The PMU-Based EMS System at TNB 456
 - 18.2.1 Overview of the PMU-Based EMS Platform 456
 - 18.2.2 System Architecture and Interface with EMS and PDC 457
 - 18.2.3 TNB PMU ROSE System Facts 457
- 18.3 LSE POM Server 458
 - 18.3.1 Methodology Used in LSE POM Server 458
 - 18.3.1.1 Linear State Estimation (LSE) 458
 - 18.3.1.2 Observability Analysis 458
 - 18.3.1.3 Bad Data Analysis 458
 - 18.3.1.4 Event Analysis 459
 - 18.3.1.5 PMU-Based State Estimator Case Creation 459
 - 18.3.2 LSE POM Server Analysis Framework 459
- 18.4 Cascading Analysis as LSE Use Case 461
 - 18.4.1 Cascading Analysis Without Remedial Actions 461
 - 18.4.2 Cascading Analysis with Remedial Actions 463
 - 18.4.2.1 Cascading Analysis Framework Using Remedial Actions: Approach 1 463
 - 18.4.2.2 Cascading Analysis Framework Using Remedial Actions: Approach 2 465
 - 18.4.2.3 Cascading Analysis Framework Using Remedial Actions: Approach 3 465
 - 18.4.3 Ranking Cascading Outages 467
- 18.5 Situational Awareness: Practical Visualization of Results 470
 - 18.5.1 PMU Viewer 470
 - 18.5.1.1 Visualization of PMU Measurements and LSE Results 471
 - 18.5.1.2 Displaying Bad Data and Events 471
 - 18.5.1.3 Event Notification and Alarm 472
 - 18.5.2 Cascading Viewer 473
- 18.6 Testing the PMU-Based EMS 475
 - 18.6.1 Test System Architecture 475
 - 18.6.1.1 Real-Time Power System Simulator (RTPSS) 475
 - 18.6.1.2 Custom Driver/Module 476
 - 18.6.1.3 Linear State Estimator 477

- 18.6.1.4 External Application..... 477
- 18.6.1.5 Database..... 478
- 18.6.2 Test Setup Using Real-Time Digital Simulator..... 478
 - 18.6.2.1 Master Subsystem 479
 - 18.6.2.2 Acquisition and Control Subsystem..... 480
- 18.6.3 Performance Analysis 480
 - 18.6.3.1 Estimating True Values Using LSE..... 480
 - 18.6.3.2 LSE Bad Data Detection 481
 - 18.6.3.3 LSE Event Detection 481
 - 18.6.3.4 Real-Time Closed-Loop Test..... 484
- 18.6.4 Using Real-Time Field PMU Data 490
- 18.7 Lessons Learned 490
- 18.8 Future Work and Conclusions 493
 - 18.8.1 Future Work 493
- 18.9 Conclusion 494
- References..... 495

19 Linear State Estimator for the Control Room: AEP’s Experience..... 497

Horacio Silva-Saravia, Samantha Whalen, Mingyu Wang,
 Backer Abu-Jaradeh, Jon Koutsourais, Yidan Lu,
 and Pedro Aneses Nieves

- 19.1 American Electric Power’s LSE 497
 - 19.1.1 Industry Need 497
 - 19.1.2 AEP’s Project Background..... 498
 - 19.1.3 LSE Components and Architecture 498
 - 19.1.3.1 Topology Processing 499
 - 19.1.3.2 Observability Analysis 500
 - 19.1.3.3 LSE Algorithm..... 500
 - 19.1.3.4 LSE-Based Automatic Bad Data Identification 503
 - 19.1.3.5 Architecture and Data Flow 504
- 19.2 AEP’s LSE Integration and Maintenance..... 505
 - 19.2.1 LSE Model 505
 - 19.2.1.1 Network Model 505
 - 19.2.1.2 PMU Mapping Information 507
 - 19.2.1.3 RTO’s Model Merging 508
 - 19.2.1.4 Automatic Maintenance of Extended Observability..... 508
 - 19.2.2 One-Line Diagrams Visualizations 510
 - 19.2.2.1 Overview Diagrams Integration..... 510
 - 19.2.2.2 Substation Diagrams Integration 510
 - 19.2.2.3 One-Line Diagram Configurations..... 511

19.2.3	Displays and Alarm Configurations.....	512
19.2.3.1	Display Types.....	512
19.2.3.2	Alarm Configurations.....	513
19.3	Benefits of LSE at AEP.....	514
19.3.1	Extended Observability.....	514
19.3.2	Situational Awareness.....	516
19.4	Next Steps for LSE Adoption in the Control Center.....	516
19.4.1	Proposed Training Plan.....	516
19.4.2	Additional Challenges.....	517
19.4.2.1	Customization on Products to Facilitate Control Room Functions.....	517
19.4.2.2	Standardization of Cross Department Coordination.....	518
19.5	Conclusions.....	518
	References.....	519
20	Implementation of Distribution Linear State Estimator: ComEd Experience.....	521
	Shikhar Pandey, Marianna Vaiman, Michael Vaiman, and Farnoosh Rahmatian	
20.1	Overview of ComEd and Its Bronzeville Community Microgrid.....	521
20.1.1	Overview of ComEd.....	521
20.1.2	Bronzeville Community Microgrid.....	522
20.1.3	Need for Real-Time Situational Awareness Platform.....	523
20.2	DLSE Software Platform for Practical Real-Time Implementation.....	524
20.2.1	Purpose of the DLSE Platform.....	524
20.2.2	Overview of the DLSE Platform.....	524
20.2.3	Importance of the Accuracy of State Estimation.....	526
20.3	Bad Data Detection and Conditioning.....	526
20.3.1	Synchrophasor Data Flow and Challenges.....	526
20.3.2	Bad Data Types Processed by DLSE.....	528
20.3.2.1	Outlier Magnitude Threshold.....	530
20.3.2.2	PMU Status Error.....	530
20.3.2.3	PMU Is Not Available.....	530
20.3.2.4	Stale Data.....	530
20.3.2.5	“Inaccurate” Data.....	531
20.4	RTDS Setup for Validating Distribution Linear State Estimator.....	531
20.4.1	Test Setup.....	531
20.4.2	Simulation: Bad Data Creation in RTDS.....	531