Power Electronics and Power Systems

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Experiences on Use of State Estimator in Power System Operations

Springer

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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.

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Contents