STATE ESTIMATION IN ELECTRIC POWER SYSTEMS
A Generalized Approach

A. Monticelli

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A. MONTICELLI
University of Campinas, Unicamp

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To Isadora

Foreword

Since it was championed three decades ago by Schweppe and others, state estimation for the real-time modeling of the electric power transmission network has remained an extremely active and contentious area. At the last count, there have been around a thousand research and development publications on new and improved methods. More recently, these have promoted dynamic, distributed and non-WLS (Weighted Least Squares) approaches.

Regardless, as I write this, centralized single-snapshot WLS estimation of the transmission network is universally established in the electric power industry. It is installed, or is scheduled to be installed, in virtually all Energy Management Systems (EMS) in the world.

The present book could not be more timely. It uniquely provides, at advanced text book level, a comprehensive anatomy of modern electric power system WLS state estimation theory and practice. It deals with everything of significance in this field, from network and power flow basics, to observability theory, to matrix solution methods, to bad data analysis, and as far as emerging technologies such as combinatorial bad data analysis and multiple-snapshot estimation. The reader can obtain an excellent, realistic grasp of the area, and even, with meticulous attention to detail, can approach specialist level.

In the early classical days of power system state estimation, the problem was formulated simply as the statistical averaging of telemetered measurements, in a network of accurately known impedances and topology. The network states (bus voltage magnitudes and angles) were declared observable or not, based on a relatively simple analysis of telemetered flow, injection and voltage measurements. A power flow model of the network was thus constructed, with any defective measurements detected, identified, and corrected or eliminated. Even this idealized formulation was (and is) not trivially solvable, particularly in the presence of mixed measurements, multiple bad measurements and poor mathematical conditioning of the problem. And unfortunately, the state estimation problem is not this simple.

Over the years, the focus of power system state estimation has shifted towards a more holistic approach. This term, borrowed from the medical field, implies utilizing all the available data. The present books author, Professor Alcir Monticelli, has been a prime mover in this trend. He and others have insisted that, in order to construct the best power flow model, all data sources must be regarded as subject to statistical error, including device statuses and impedance values. This is the underlying message of the books title: Generalized State Estimation. A generalized approach takes into account that the network impedances and topology are not accurately known. And many measurements, particularly in the external network, are just crude predictions. Likewise, all other potentially imprecise data sources, including transformer taps, phase shifter angles, voltage regulation set points, interchange schedules, equipment limits, and plausibility criteria (e.g. non-negative loads) have to be factored into the estimation process.

Electric power industry deregulation has transformed state estimation from an important application into a critical one. Most individual utilities transmission networks are being amalgamated into larger regional not for profit network infrastructures. Power transfers now take place over electrical distances and in directions for which the network was never designed. Competitive, monetary factors are the sole drivers of the process, within electrical operating limits. But the transmission network has finite capacity. Therefore the system operator has to make equitable, security-related, congestion management decisions to curtail or deny power transfer rights. This is a critical commercial issue. It has to be founded and justified on a precise model of the power system, derived from the state estimation process. Moreover, accurate state estimation is the foundation of Locational Marginal Pricing methodologies for transmission congestion management costing.

These regional networks can be huge (a recent such EMS specification calls for the supervision of 100,000 buses). Computationally efficient state estimation solutions are therefore essential. This book deals with all the related issues - sparse matrix solution technology, including ordering and network reduction, and the robust orthogonal transformation approaches. In principle, state estimation in electric power systems is ubiquitous. It is not limited to transmission level modeling. Modern Distribution Management Systems and, in some cases, more vertical network management, need state estimation to reach further into the lower voltage network. Even off-line studies, requiring the assemblage of a multi-area model from disparate data sources, can benefit from the data integrating and reconciling capabilities of state estimation.

The scope of the present book is close to monumental. It crystalizes 30 years of electric power system WLS state estimation theory and practice into the modern essentials, presented at advanced text book level. Alcir Monticelli's multiple, focused R&D contributions to state estimation are cumulatively the most important in the area. These techniques have been adopted by state estimation developers worldwide. Moreover, Monticelli has the credentials of being a designer and developer of industrial-grade state estimation software that is used in the USA, South America and elsewhere. He therefore brings important insights to the book and, perhaps as profoundly, omits irrelevancies and side issues. My colleagues and I have had the privilege of working with him for 22 years.

Brian Stott
PCA Corporation
Mesa, Arizona, USA

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Contents

1 REAL-TIME MODELING OF POWER NETWORKS

A real-time model is a quasi-static computer-based mathematical representation of the current conditions in a power network. This model is extracted at intervals from "snapshots" of real-time measurements (analog measurements and the status of switching devices) as well as from static network data (basic configuration and parameters). State estimation is the key function for obtaining such a real-time network model. A more complete understanding of state estimation is becoming more important than in the past due both to new modeling needs and to changes induced by deregulation. This chapter reviews the main concepts involved in state estimation and economy-security functions carried out by the Energy Management System (EMS).

1.1 SECURITY CONCEPTS

The concept of network security is associated with the probability of the maintenance of an adequate supply. The higher the security level, the lower the probability of loss of load. Security oriented control actions are thus aimed at avoiding blackouts and equipment damage.

A contingency is a loss of transmission equipment and/or generation units. Contingency analysis involves the analysis of possible contingencies that are likely to occur to detect the potentially harmful ones, i.e., contingencies that, if they occurred, would lead the system into a state of emergency. Both single and