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Zhengshuo Li

Distributed Transmission-Distribution Coordinated Energy Management Based on Generalized Master-Slave Splitting Theory

Doctoral Thesis accepted by
Tsinghua University, Beijing, China

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This book is dedicated to my parents, Zuoqin Li and Shumei Wang, and to my wife Jiaqi Ji who encouraged me to finish this book.

Supervisor's Foreword

Dr. Zhengshuo Li was my Ph.D. student from 2011 to 2016. He got the Bachelor degree with honors in 2011 and the Ph.D. degrees with honors in 2016, both from Department of Electrical Engineering, Tsinghua University. His Ph.D. dissertation focused on Coordinated Energy Management of Integrated Transmission and Distribution Power Systems. His work is theoretically innovative and technically sound, providing a promising solution to the infamous challenges to power systems in the context of distributed energy resource (DER) integration. His research work has been published by several prestigious international journals, and he was awarded Excellent Doctoral Dissertation of Tsinghua University in 2016. Recently, he was also awarded Special-Class China Postdoctoral Science Foundation, which is a high honor for young scholars in China: as a matter of fact, only eight scholars including him in electrical engineering won this foundation this year.

As for this book, first, I would like to stress that it aims to provide a solution to solving the challenges brought by DERs to power system operation, which is a widely concerned issue for nowadays power systems. When Dr. Zhengshuo Li started his Ph.D. student career, I advised him to focus on this widely concerned topic and to find a both theoretically and technically sound solution. When we went further, we realized that coordination between transmission and distribution power system operation, which was conventionally ignored by most scholars and engineers, might be an excellent solution to the challenges. After discussing with other researchers and reading up-to-date reports from the industry, we believed that a distributed implementation of Transmission–Distribution Coordinated Energy Management (TDCEM) will be a promising solution to the DER challenges. In 2014, Dr. Zhengshuo Li commenced his study on the TDCEM and finished his dissertation in Chinese in 2016 and finally this English book.

Second, I would like to point out the prominent features of this book. First, this book proposes a new distributed optimization theory called Generalized Master–Slave Splitting (G-MSS). In comparison with other distributed optimization theories, this theory fully exploits the heterogenous operational features of transmission and distribution power systems and thus enjoys a faster convergency. Moreover, the coordination mechanism indicated by the G-MSS theory conforms to the demands of field power system operation. Second, this book closely correlates mathematics and the physics in power systems. For example, the sensitivity of an optimization problem in some cases can be physically understood as a power system equivalent that is originally derived from the physics in circuits, and the convergency of a distributed optimization method with such an equivalent included is proved to be significantly enhanced. This is an interesting finding by which a reader may be inspired. Third, this book presents a series of distributed transmission–distribution coordination functions, such as contingency analysis, static voltage stability assessment, economic dispatch, and optimal power flow. These functions are central to a TDCEM system, guaranteeing the security and economy of power system operation. Thus, this book presents readers with a primary structure of a distributedly implemented TDCEM system.

Lastly, I would like to conclude by recommending this book to readers who are exploring effective methods to resolve DER challenges to power system operation and/or who are interested in a distributed optimization theory and its application in power systems.

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Preface

Conventionally, transmission and distribution power systems are separately operated by Transmission Control Centers (TCCs) and Distribution Control Centers (DCCs) via different energy management systems, respectively. This separated management mode makes a TCC and a DCC "blind" to each other. Although this mode has been smoothly functioning for a long time, it is now facing challenges from increasing penetration of Distributed Energy Resources (DERs) and feeder automation. For example, as reported by CAISO, ENTSO-E, and other publications, this separated energy management mode is incapable of accurately detecting the voltage collapse point of the entire power system and fails in accurately reflecting the true post-contingency state of the entire system, and in optimally dispatching the controllable devices to mitigate line congestions and to reduce the entire system operational costs.

To overcome these challenges to the security and economy of power system operation, Transmission–Distribution Coordinated Energy Management (TDCEM) may be an effective technical solution if a suitable distributed coordination mechanism is designed, which fits the practical one-to-many relationships of a TCC and DCCs and allows a minimal degree of boundary nodal information to exchange between the control centers. This book proposes a new distributed optimization theory for the TDCEM problem and a series of distributedly implemented transmission–distribution coordination functions in a TDCEM system.

In Chap. 2, a Generalized Transmission–Distribution Coordination Model (G-TDCM) is established, which is demonstrated to be universally applicable to almost all the main functions, e.g., state estimation, power flow, contingency analysis, economic dispatch, and optimal power flow, regarding the TDCEM.

In Chap. 3, a Generalized Master–Slave Splitting (G-MSS) theory is proposed to heterogeneously decompose the G-TDCM into a transmission optimization subproblem and a group of distribution optimization subproblems, which can be distributedly solved by a TCC and DCCs, respectively. Only generalized boundary state variables and generalized boundary injection are needed to exchange between the control centers in the iteration. The G-MSS theory is proved to have sure optimality and convergency properties, and moreover it provides a clear picture of the coordination mechanism for the TDCEM. Notably, if the subsystem response functions are added into the subproblems, the convergency of the G-MSS theory can be further improved.

In Chap. 4, a Global-Power-Flow-Based Transmission Contingency Analysis (GTCA) method, which considers the impact of distribution-side power flow on the transmission contingency analysis, is proposed. A distributed GTCA method is derived from the G-MSS theory, and several speeding-up approaches are proposed. Case study confirms that GTCA contributes to a more reliable security evaluation result than conventional contingency analysis methods.

In Chap. 5, static Transmission–Distribution Voltage Stability Analysis (TDVSA) is proposed. The impact of distributed generation' low-voltage tripping on the static voltage stability of an integrated transmission–distribution system is theoretically analyzed and numerically verified. A distributed TDVSA method is also derived from the G-MSS theory. Numerical case study confirms that distributed generation' low-voltage tripping has a notable impact on both transmission- and distribution-side voltage stability assessment, and separatedly performed transmission VSA and distribution VSA may produce erroneous assessments. The proposed TDVSA method is able to produce accurate results.

In Chap. 6, Transmission–Distribution Coordinated Economic Dispatch (TDCED) is studied. Two distributed TDCED methods are derived from the G-MSS theory, and thus both of them have guaranteed optimality and convergency. Moreover, how to consider security constraints in TDCED is discussed and a distributed solution to security-constrained TDCED problem is designed based on the G-MSS theory. Case study confirms that TDCED contributes to a more economical generation schedule, congestion mitigation, and a rational evaluation of locational marginal prices. In addition, it is demonstrated that both of the proposed distributed TDCED methods require much fewer iterations for converging than other typical decomposition methods do. The performances of the proposed TDCED methods are also robust against the scale of problems.

In Chap. 7, Transmission–Distribution Coordinated Optimal Power Flow (TDOPF) is investigated. A distributed TDOPF method is derived from the G-MSS theory. Although the TDOPF model is nonconvex, the local optimality and local convergency properties of this method are guaranteed owing to the G-MSS theory. Case study confirms that TDOPF alleviates the post-outage overloading of TPS lines at a cheaper generation cost and mitigates DPS-side over-voltage issues without any DG curtailment. In addition, in comparison with other distributed methods, the G-MSS-based distributed TDOPF method converges to the optimal solution with the fewest iterations.

To summarize, this book aims to provide an efficient and distributed computation method for an integrated transmission–distribution power system to guarantee the security and economy of its operation in the context of DER integration. This book may interests readers who are searching for theoretically and technically sound methods to resolve DER challenges to power system operation and/or who are interested in a distributed optimization theory for a multi-area power system.

Shenzhen, China Zhengshuo Li

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I would like to acknowledge Prof. Hongbin Sun who was my Ph.D. Supervisor in Tsinghua University, Beijing, China from 2011 to 2016, Associate Professor Qinglai Guo in Tsinghua University, and Associate Professor Jianhui Wang in Southern Methodist University for their helpful advice on my research. Particularly, Associate Professor Jianhui Wang advised me to resolve the deficiency in the current transmission contingency analysis method when I was a visiting student in Argonne National Laboratory, Chicago, IL, USA, in 2014. The two professors in Tsinghua University encouraged me to develop a generalized solution method that is applicable to main functions in EMS.

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Contents

Abbreviations

CA	Contingency Analysis
DCC	Distribution Control Center
DG	Distributed Generation
DMS	Distribution Management System
D-VSA	Distribution Voltage Stability Assessment
ED	Economic Dispatch
EMS	Energy Management System
G-MSS	Generalized Master–Slave Splitting Theory
GPF	Global Power Flow
GTCA	GPF-Based Transmission Contingency Analysis
G-TDCM	Generalized Transmission–Distribution Coordination Model
HGD	Heterogeneous Decomposition
KKT	Karush–Kuhn–Tucker
OPF	Optimal Power Flow
SE	State Estimation
TCC	Transmission Control Center
TDCED	Transmission–Distribution Coordinated Economic Dispatch
TDCSE	Transmission–Distribution Coordinated State Estimation
TDCUC	Transmission–Distribution Coordinated Unit Commitment
TDOPF	Transmission–Distribution Coordinated Optimal Power Flow
TDPF	Transmission–Distribution Coordinated Power Flow
TDVSA	Transmission–Distribution Voltage Stability Assessment
T-VSA	Transmission Voltage Stability Assessment