Unit Commitment in Electric Energy Systems

Miguel F. Anjos
Department of Mathematics and Industrial Engineering
GERAD & Polytechnique Montreal
anjos@stanfordalumni.org

Antonio J. Conejo
Department of Integrated Systems Engineering
Department of Electrical and Computer Engineering
The Ohio State University
conejonavarro.1@osu.edu

now
the essence of knowledge
Boston — Delft

Full text available at: http://dx.doi.org/10.1561/3100000014

Foundations and Trends® in Electric Energy Systems

Published, sold and distributed by:
now Publishers Inc.
PO Box 1024
Hanover, MA 02339
United States
Tel. +1-781-985-4510
www.nowpublishers.com
sales@nowpublishers.com

Outside North America:
now Publishers Inc.
PO Box 179
2600 AD Delft
The Netherlands
Tel. +31-6-51115274

The preferred citation for this publication is

M. F. Anjos and A. J. Conejo. *Unit Commitment in Electric Energy Systems.* Foundations and Trends® in Electric Energy Systems, vol. 1, no. 4, pp. 220–310, 2017.

This Foundations and Trends® issue was typeset in LaTeX using a class file designed by Neal Parikh. Printed on acid-free paper.

ISBN: 978-1-68083-370-6
© 2017 M. F. Anjos and A. J. Conejo

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, mechanical, photocopying, recording or otherwise, without prior written permission of the publishers.

Photocopying. In the USA: This journal is registered at the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923. Authorization to photocopy items for internal or personal use, or the internal or personal use of specific clients, is granted by now Publishers Inc for users registered with the Copyright Clearance Center (CCC). The 'services' for users can be found on the internet at: www.copyright.com

For those organizations that have been granted a photocopy license, a separate system of payment has been arranged. Authorization does not extend to other kinds of copying, such as that for general distribution, for advertising or promotional purposes, for creating new collective works, or for resale. In the rest of the world: Permission to photocopy must be obtained from the copyright owner. Please apply to now Publishers Inc., PO Box 1024, Hanover, MA 02339, USA; Tel. +1 781 871 0245; www.nowpublishers.com; sales@nowpublishers.com

now Publishers Inc. has an exclusive license to publish this material worldwide. Permission to use this content must be obtained from the copyright license holder. Please apply to now Publishers, PO Box 179, 2600 AD Delft, The Netherlands, www.nowpublishers.com; e-mail: sales@nowpublishers.com

Full text available at: http://dx.doi.org/10.1561/3100000014

Foundations and Trends® in Electric Energy Systems

Volume 1, Issue 4, 2017

Editorial Board

Editorial Scope

Topics

Foundations and Trends® in Electric Energy Systems publishes survey and tutorial articles on the following topics::

- Advances in power dispatch
- Demand-side and grid scale data analytics
- Design and optimization of electric services
- Distributed control and optimization of distribution networks
- Distributed sensing for the grid
- Distribution systems
- Fault location and service restoration
- Integration of physics-based and data-driven modeling of future electric energy systems
- Integration of Power electronics, Networked FACTS
- Integration of renewable energy sources
- Interdependence of power system operations and planning and the electricity markets
- Microgrids: design, optimization, and stability
- Modern grid architecture
- Power system analysis and computing
- Power system dynamics
- Power system operation
- Power system planning
- Power system reliability
- Power system transients
- Security and privacy
- Stability and control for the whole multi-layer (granulated) network with new load models (to include storage, DR, EVs) and new generation
- System protection and control
- The new stability guidelines and control structures for supporting high penetration of renewables
- Uncertainty quantification for the grid
- System impacts of HVDC

Information for Librarians

Foundations and Trends® in Electric Energy Systems, 2017, Volume 1, 4 issues. ISSN paper version 2332-6557. ISSN online version 2332-6565. Also available as a combined paper and online subscription.

Foundations and Trends® in Electric Energy Systems
Vol. 1, No. 4 (2017) 220–310

DOI: 10.1561/3100000014

Unit Commitment in Electric Energy Systems

Miguel F. Anjos
Department of Mathematics and Industrial Engineering
GERAD & Polytechnique Montreal
anjos@stanfordalumni.org

Antonio J. Conejo
Department of Integrated Systems Engineering
Department of Electrical and Computer Engineering
The Ohio State University
conejonavarro.1@osu.edu

Full text available at: http://dx.doi.org/10.1561/3100000014

Contents

Abstract

The unit commitment problem is a fundamental problem in the electric power industry. The objective of unit commitment is to determine an optimal schedule for each generating unit so that the demand for electricity is met at minimum cost for the system as a whole. This tutorial presents the most relevant mathematical optimization models for the unit commitment problem. It is intended as a starting point for learning about this important problem, and thus only the key technical details are included. Likewise, we point out selected references instead of providing a comprehensive literature review of the area.

M. F. Anjos and A. J. Conejo. *Unit Commitment in Electric Energy Systems*. Foundations and Trends® in Electric Energy Systems, vol. 1, no. 4, pp. 220–310, 2017.
DOI: 10.1561/3100000014.

1

Introduction to the Unit Commitment Problem

The unit commitment (UC) problem addresses a fundamental decision in the operation of a power system, namely determining the schedule of power production for each generating unit in the system so that the demand for electricity is met at minimum cost. The schedule must also ensure that each unit operates within its technical limits; these typically include ramping constraints and minimum uptime/downtime constraints. Units that are scheduled to produce electricity during a given time period are said to be *committed* for that period.

Various jurisdictions solve UC on a daily basis. In particular, it is the standard tool for clearing spot markets, and particularly day-ahead markets in the USA. In North American jurisdictions without markets, the system operators use UC to determine the day-ahead commitments and dispatches.

The UC problem can be formulated as a mixed-integer nonlinear optimization problem, and it is generally large-scale and nonconvex. It is NP-hard in general, but its practical importance has motivated a tremendous amount of research dedicated to techniques for computing global optimal solutions. This is both because of the significance of the operational costs and because in competitive market environments, the nonconvexity of the UC problem allows the existence of multiple local optimal solutions that may lead to considerably different pricing and market settlement outcomes. Indeed, a mixed-integer linear (or nonlinear but convex) optimization model of the UC problem is among the few techniques that can provide provably global optimal solutions for the commitment decisions and corresponding financial settlements. At the same time, the time available to solve the problem is a hard constraint in practice. Hence, UC is an optimization problem that is both important and challenging.

Various important aspects of UC can be integrated in a mixed-integer nonlinear optimization approach, but the time required to solve the UC models is a hard practical limitation that restricts the size and scope of UC formulations. For this reason there is no single formulation of UC; instead it is a matter of designing a formulation that incorporates the important aspects of the problem for a given context while ensuring that the resulting optimization problem can be solved to optimality, or near-optimality, in a reasonable time.

With the increasing penetration of stochastic sources of electricity in modern power systems, most notably wind and solar generation, techniques for handling uncertainty are acquiring greater importance in UC modeling. We focus our presentation on two well-known techniques for modeling uncertainty in mathematical optimization, namely stochastic optimization and robust optimization. These are by no means the only mathematical optimization techniques for handling uncertainty, but we believe that they are the most relevant in the context of UC because power system operators will always prefer approaches that enforce constraints, rather than satisfying them with some probability, which is the basis of most other approaches.

All the formulations that we present here are mathematical optimization problems. The Introduction to Optimization of the NEOS Guide provides information about the different classes of mathematical optimization problems and the software available to solve them. Most of the state-of-the-art solvers, whether commercial or open source, can be accessed for free on the NEOS Server [Czyzyk et al., 1998, Dolan, 2001, Gropp and Moré, 1997]. All the computations made in the preparation of this book were carried out on the NEOS Solver.

1.1 Outline of this Book

We introduce in the next six chapters a selection of formulations of UC that integrate different aspects of the problem. We discuss the motivation for and the detailed structure of each formulation and then recapitulate the mathematical model. Each chapter concludes with a small example, accompanied by a description of how the results illustrate the features of the corresponding formulation.

We begin in Chapter 2 with a basic formulation of UC that focuses on the modeling of the generating units and ensuring that generation meets demand (with spinning reserves). The next step is to integrate the impact of the power network; this can be done using power flow equations in either linear (DC) form (Chapter 3) or alternating current (AC) form (Chapter 5). The security of the system is a common concern. In Chapter 4 we integrate constraints to ensure that the system can cope with the failure of one of its major components.

The subsequent two chapters are concerned with modeling uncertainty in the data for UC. We consider two modeling approaches: Chapter 6 introduces a stochastic optimization approach that is based on the use of scenarios, and Chapter 7 presents a robust optimization approach that focuses on the worst-case operating conditions.

While we briefly comment in the presentation of each example on how the computational results were obtained, a detailed discussion of the computational aspects of solving each formulation is given in Chapter 8. Chapter 9 provides concluding remarks and discusses future research.

References

M. F. Anjos and J. B. Lasserre, editors. *Handbook on Semidefinite, Conic and Polynomial Optimization*. International Series in Operations Research & Management Science. Springer-Verlag, 2011.

E. Balas and M. Fischetti. Integer (linear) optimization. In T. Terlaky, M. F. Anjos, and S. Ahmed, editors, *Advances and Trends in Optimization with Engineering Applications*, chapter 5, pages 49–63. 2017.

D. Bertsimas and R. Weismantel. *Optimization Over Integers*, volume 13. Dynamic Ideas Belmont, 2005.

D. Bertsimas, E. Litvinov, X. A. Sun, J. Zhao, and T. Zheng. Adaptive robust optimization for the security constrained unit commitment problem. *IEEE Transactions on Power Systems*, 28(1):52–63, 2013.

F. Bouffard, F. D. Galiana, and A. J. Conejo. Market-clearing with stochastic security- Part I: formulation. *IEEE Transactions on Power Systems*, 20(4): 1818–1826, 2005.

R. H. Byrd, J. Nocedal, and R. A. Waltz. KNITRO: An integrated package for nonlinear optimization. In *Large-scale Nonlinear Optimization*, pages 35–59. Springer, 2006.

C. Coffrin and P. Van Hentenryck. A linear-programming approximation of AC power flows. *INFORMS Journal on Computing*, 26(4):718–734, 2014.

J. Czyzyk, M. P. Mesnier, and J. J. Moré. The neos server. *IEEE Journal on Computational Science and Engineering*, 5(3):68–75, 1998.

E. D. Dolan. The neos server 4.0 administrative guide. Technical Memorandum ANL/MCS-TM-250, Mathematics and Computer Science Division, Argonne National Laboratory, 2001.

J. Dupačová, N. Gröwe-Kuska, and W. Römisch. Scenario reduction in stochastic programming. *Mathematical Programming*, 95(3):493–511, 2003.

Y. Fu, M. Shahidehpour, and Z. Li. Security-constrained unit commitment with AC constraints. *IEEE Transactions on Power Systems*, 20(3):1538–1550, 2005.

L. L. Garver. Power generation scheduling by integer programming-development of theory. *Power Apparatus and Systems, Part III. Transactions of the American Institute of Electrical Engineers*, 81(3):730–734, 1962.

A. M. Geoffrion. Generalized Benders decomposition. *Journal of Optimization Theory and Applications*, 10(4):237–260, 1972.

W. Gropp and J. J. Moré. Optimization environments and the neos server. In M. D. Buhman and A. Iserles, editors, *Approximation Theory and Optimization*, pages 167–182. Cambridge University Press, 1997.

H. Heitsch and W. Römisch. Scenario reduction algorithms in stochastic programming. *Computational Optimization and Applications*, 24(2-3):187–206, 2003.

J. M. Morales, A. J. Conejo, and J. Pérez-Ruiz. Economic valuation of reserves in power systems with high penetration of wind power. *IEEE Transactions on Power Systems*, 24(2):900–910, 2009.

G. Morales-España, J. M. Latorre, and A. Ramos. Tight and compact MILP formulation of start-up and shut-down ramping in unit commitment. *IEEE Transactions on Power Systems*, 28(2):1288–1296, 2013.

A. L. Motto, F. D. Galiana, A. J. Conejo, and J. M. Arroyo. Network-constrained multiperiod auction for a pool-based electricity market. *IEEE Transactions on Power Systems*, 17(3):646–653, 2002.

R. P. O'Neill, P. M. Sotkiewicz, B. F. Hobbs, M. H. Rothkopf, and W. R. Stewart. Efficient market-clearing prices in markets with nonconvexities. *European Journal of Operational Research*, 164(1):269–285, 2005.

J. Ostrowski, M. F. Anjos, and A. Vannelli. Tight mixed integer linear programming formulations for the unit commitment problem. *IEEE Transactions on Power Systems*, 27(1):39–46, 2012.

M. Tawarmalani and N. V. Sahinidis. A polyhedral branch-and-cut approach to global optimization. *Mathematical Programming*, 103:225–249, 2005.

R. J. Vanderbei. *Linear Programming: Foundations and Extensions*. Springer, 2001.