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Review

Distributed optimization approaches for emerging power systems operation: A review

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ABSTRACT

Independent system operators (ISO) and regional transmission organizations (RTO) adopt centralized optimization approaches for the optimal operation of power systems, which collect all required information and perform centralized operation decisions at the central controller. As the size of power systems expends and more flexible and distributed resources from the demand side are being involved in power systems, such a centralized framework raises computation and communication concerns. Distributed optimization, as an alternative approach to solve challenges of the centralized optimization mechanism, has attracted increasing attention recently. This paper reviews existing works on distributed optimization for power systems operation. We first discuss various distributed optimization algorithms that have been studied for power systems operation, followed by a detailed literature review on adopting such distributed algorithms for major power systems operation applications including distributed economic dispatch (ED), distributed AC-optimal power flow (OPF), distributed unit commitment (UC), and other distributed applications. The advantages and barriers of applying each distributed algorithm in practice are discussed. Since the applications of distributed algorithms in practical cases largely rely on the high performance computing (HPC) platform, the application of HPC techniques on power system operation problems is also reviewed. Future research needs for effectively and efficiently promoting the practical deployment of such distributed optimization approaches in emerging power systems are identified.

Contents

Abbreviations: ADMM, alternating direction method of multipliers; AOP, alternating optimization procedure; ATC, analytical target cascading; APP, auxiliary problem principle; BD, benders decomposition; DR, demand response; ED, economic dispatch; ISO, independent system operator; NYISO, New York ISO; CASIO, California ISO; ISONE, ISO New England; MISO, Midcontinent ISO; HPC, high performance computing; RTO, regional transmission organizations; PVM, parallel virtual machine; MPI, message passing interface; GPU, graphics processing units; ICC, incremental cost consensus; KKT, Karush–Kuhn–Tucker; LR, Lagrangian relaxation; ME, marginal equivalent; OPF, optimal power flow; OCD, optimal condition decomposition; SCUC, security constrained unit commitment; UC, unit commitment; SDP, semi-definite programming; MINLP, mixed-integer nonlinear problem.

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1. Introduction

Optimal operation problems in different areas are commonly solved in a centralized framework [1,2], and power system is not an exception [3]. The centralized optimization framework has been pervasively utilized in power systems operation, which collects all required information and performs centralized operation decisions at the central controller. However, such a centralized framework is facing critical challenges in emerging power systems.

(1) The first one is the communication and computation challenges for large-scale power systems. As the size of power systems expends, the communication requirement for collecting relevant information and the computational complexity for solving large-scale optimization problems (e.g. security-constrained unit commitment (SCUC)) will increase significantly. Ref. [4] reported a total of 7 market disrupt events relevant to real-time unit commitment (UC) and 35 disrupt events on real-time economic dispatch (ED) from 16 January, 2012 to 15 February, 2012 in CAISO. The disrupt events were mostly caused by software application failures and broadcast failures. Ref. [5] analyzed the complexity for solving the SCUC problem of the MISO market with 43,962 network buses and 1390 generating units. When solving the SCUC problem in a centralized manner, MISO will receive a matrix of data with 18,1474 rows and 48,9155 columns from different participants. Ref. [5] reported that although the state-of-the-art solvers can efficiently handle most cases, there are always occasions that the solvers have difficulty in finding good solutions and require significant computational time. This issue could become more severe as the size of power systems increases and more flexible and distributed resources from the demand side are being involved in power systems. Ref. [6] compared the communication requirements of the centralized and the distributed frameworks, and the simulation result of an IEEE-118 bus system indicated that by moving from the centralized topology to a decentralized one, the volume of communication reduced significantly from 275.68 to 195 million bit-hops.

(2) The second one is political and technical challenges for the multi-area coordination. The growing interconnection of regional electricity infrastructures and the large-scale integration of renewable energy demand for a coordinated multi-area scheduling to achieve the overall reliability and economic efficiency. For the multi-area coordination in which individual regions are operated by different ISOs/RTOs, the centralized optimization framework is unlikely to be practical because of political difficulties for sharing interregional data and technical difficulties for building and solving complicated models. It is also the case when coordinating an ISO with multiple utility companies that operate distribution systems within the ISO territory. In Ref. [7], the challenges of defining fair decision-making strategies for individual system operators of the interconnected electricity infrastructure were analyzed. Ref. [8] indicated that roughly 50% of the time in 2009, power flows of tie lines connecting different ISOs were in the wrong direction. The main reason is that each ISO is unwilling to disclose financial information, system topology, or control regulations to the other ISOs, and in turn transactions are scheduled independently and cannot properly reflect the benefit to the entire system.

Considering these challenges, distributed optimization as an alternative approach has drawn increasing attention. In the distributed optimization framework, a large-scale power system is divided into small-scale sub-regions, and subproblems for individual sub-regions can be efficiently solved and effectively coordinated to obtain a final solution to the original problem. In addition, local subproblems can be solved simultaneously in a parallel manner with the help of high-performance computing (HPC) techniques, which can further enhance the computational performance of distributed optimization. HPC has been utilized in power system applications for improving computation efficiency [9]. However, due to difficulties in allocating tasks to individual processing units through partitioning [10], HPC is mostly limited to solving large-scale linear and non-linear equations in the transient stability based contingency analysis [11–13] and the power flow calculation [14,15]. Indeed, distributed optimization provides a decomposition structure that perfectly suits for HPC. In distributed optimization framework, local subproblems can be directly distributed to individual processing units, e.g. individual cores of a multi-core CPU or individual stand-alone computers in a cloud network of multiple computers.

Another advantage of distributed optimization framework is that the communication requirement could be significantly reduced, since only limited information needs to be exchanged among adjacent sub-regions and/or between sub-regions and the central controller during the optimization procedure. Moreover, compared to the centralized method, distributed optimization framework is more flexible and adaptive with respect to the changes of systems, especially in view that topologies of the electricity grid and the communication infrastructure in the smart grid are likely to be more dynamic.

Over the years, various schemes have been explored for solving power system operation problems in a distributed fashion, varying from the incremental cost consensus (ICC) based methods [16–22] to Lagrangian relaxation (LR) based approaches [27–37]. Some approaches coordinate subproblems via price and cost signals [16–26], while others adopt physical information such as voltage (magnitude and voltage angle) of boundary buses and tie-line power flows [35,36,38,41–44]. In literature, performances of various distributed models are usually compared to the centralized method, while the comparison among different distributed schemes is limited. Indeed, various distributed algorithms could present different convergence properties and require varying communication supports (e.g., from a partially distributed scheme in which individual subproblems communicate directly with a central controller to a fully distributed scheme without a central coordinator in which individual subproblems communicate directly with each other). On the other hand, the mathematical essence of certain distributed schemes may be the same and they would face similar challenges in practical applications (e.g., auxiliary problem principle (APP) [28] and alternating direction method of multiplier (ADMM) [29–31] are both augmented LR based approaches, and the global convergence is guaranteed only if a problem is convex).

To the best knowledge of the authors, distributed optimization algorithms have not been widely applied in practice for power industry. One possible reason is that certain distributed optimization algorithms with weak convergence properties may require many iterations and in turn increase computational burden beyond the limit of practical interest for power industry. Thus, it is necessary to review state-of-the-art distribute algorithms with