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Fully decentralized multiarea reactive power optimization considering practical regulation constraints of devices☆

Jinbo Huang, Zhigang Li*, Q.H. Wu

School of Electric Power Engineering, South China University of Technology, Guangzhou 510640, China

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ABSTRACT

Reactive power optimization is essentially finding the optimal power flow for optimizing the voltage profile and power flow in the steady state. Considering that the operation of devices is restricted by their service lifetimes and regulations, dynamic reactive power optimization (DRPO) is formulated as a mixed-integer nonlinear programming problem considering the practical regulation constraints of devices. To preserve the control independence and information privacy of the distributed subnetworks, a three-stage programming approach is proposed to achieve a fully decentralized solution to the DRPO problem of the multiarea power system. In addition to incorporating optimality condition decomposition, the decentralized DRPO method includes three stages for addressing the difficulty in handling the discrete variables, and it can achieve a fully distributed solution for the multiarea DRPO problem, with only minor boundary information to be exchanged. A forward-backward-pass dynamic programming approach with computational complexity of polynomial order is utilized to solve the stepwise fitting problem. The simulation results for three test systems demonstrate that the proposed decentralized method can obtain a high-quality solution in a decentralized manner with promising computation performance considering the practical regulation constraints.

1. Introduction

Reactive power optimization (RPO) is essentially finding the optimal power flow (OPF) that determines all types of controllable variables, such as the tap ratios of transformers and the reactive power outputs of generators and shunt capacitors/reactors (SCRs), to optimize the steady-state power flow. RPO is conducted to minimize transmission losses or other appropriately defined objective functions while satisfying a given set of physical and operating constraints. Since the tap ratios of transformers and the reactive power outputs of SCRs are typically discrete values, the RPO is commonly modeled as a mixed-integer nonlinear programming (MINLP) problem. However, in the distribution systems, RPO can be formulated as a mixed-integer linear programming problem that can be efficiently solved to its global optimum [1–3]. A number of optimization techniques have been proposed to solve the RPO problem. These techniques can generally be divided into two types of approaches: the first type includes intelligent searches, such as genetic algorithms [4], particle swarm optimization methods [5] and dynamic multi-group self-adaptive differential evolution algorithm [6], and the other type includes conventional mathematical programming methods, such as successive quadratic programming methods [7] and interior-point methods [8,9]. Recently, multi-objective optimization approaches for reactive power dispatch have become popular [10,11]. Optimizing multi-objective reactive power dispatch in power systems is an effective way of improving voltage quality, decreasing active power losses and increasing voltage stability margin [12].

Conventionally, static RPO only considers a single system state at a certain time period. In fact, discrete controllable devices (e.g., SCRs and transformer taps) are controlled via switching on/off, the operation of which is restricted by their service lifetimes and regulations. Hence, dynamic reactive power optimization (DRPO) [13,14] has been formulated considering the intertemporal constraints on the operating times of discrete switching devices. DRPO is a large-scale, multiperiod and complex MINLP problem that is difficult to solve directly. Various techniques have been proposed to solve the DRPO problem. In [15], second-order cones are employed to relax the non-convex power flow equations to obtain a mixed integer second order cone programming

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* Corresponding author.
E-mail address: lizg16@scut.edu.cn (Z. Li).

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model for the DRPO problem, and a sensitivity-based relaxation and decomposition method is proposed to further improve the computational performance. A fuzzy-based RPO model is proposed in [16], which considers constraints on the number of switching operations of control devices, and a simulated annealing search technique is used to solve the problem. Reference [17] proposes an algorithm based on a nonlinear interpoint method and discretization penalties to solve this problem. In addition to the maximum allowable regulation time constraint, there are some other practical regulation constraints of devices, such as the minimum regulation time interval and the minimum regulation threshold constraints. In practice, to avoid frequent operation of the devices, the regulation times, regulation time interval and regulation threshold of the devices are restricted by the system operators. The maximum allowable regulation time constraint limits the total regulation times of devices, which should be less than the maximum allowable regulation times. Due to the limit of the minimum regulation time interval constraint, the regulation states of the devices need to be maintained for a certain period of time, which means that frequent regulation of the devices in a short time period is not permitted. In addition, due to the limit of the minimum regulation threshold constraint, the changes of the devices should be greater than their regulation thresholds, which avoids frequent operation of the devices for some tiny changes. However, these practical regulation constraints are not properly considered in the recent literature.

Modern transmission power systems are divided into various controlling regions. Generally, each regional network, or subnetwork, represents an independent utility that has its own operating criteria and separate transmission system operator (TSO). Under the electricity market environment, the information barriers between subnetwork control centers further impede the transferring and sharing of data. However, if each TSO controls the power network in its own region without considering the interactions with the other parts of the interconnected power systems, control conflicts would occur between interconnected regional systems. Hence, it is necessary to coordinate solutions of different individual TSOs to achieve the overall optimal solution. Decomposition techniques can be applied to carry out the solution while preserving the dispatch independence of the distributed subnetworks.

Many studies have focused on the distributed OPF/RPO. A fully decentralized OPF algorithm for multi-area power systems based on the distributed interior point method is presented in [18]. Other popular decomposition algorithms, such as alternating direction method of multipliers (ADMM) [19–21] and Benders decomposition [22], have also been implemented to solve the decentralized OPF problem. Benders decomposition requires a central coordinator to solve the master problem or to update the tie-line flow. However, it is occasionally impractical because such a coordinator may not exist. Although works [19–21] have attempted to research a fully decentralized ADMM without the coordinator, the algorithm requires a long computational time due to the existence of the multiplier updating process. In addition, external network equivalence techniques are applied to multiarea RPO in [23,24]. The optimal condition decomposition (OCD) algorithm [25] has been successfully implemented to solve a number of optimization problems in power systems, such as the OPF problem [26], dynamic economic dispatch problem [27] and the combined heat and power dispatch problem [28]. The OCD algorithm requires only minor boundary information to be exchanged without any central coordinator. The OCD algorithm is simple, efficient and practical. Most importantly, the OCD algorithm can guarantee the privacy of data during decision making and can achieve a fully distributed solution for the multiarea optimization problem.

However, the discrete variables and the practical regulation constraints of devices are not considered in recent studies, and few studies have focused on the distributed DRPO problem. In addition, the standard OCD algorithm cannot effectively handle mixed-integer programs in a fully decentralized manner. To bridge this gap, this paper introduces a three-stage algorithm that incorporates OCD to solve the multiarea DRPO problem considering the practical regulation constraints of devices. The contributions of this paper are threefold:

(1) A DRPO model is formulated considering the practical regulation constraints of devices, which include the maximum allowable regulation time, minimum regulation time interval and minimum regulation threshold constraints.
(2) A forward-backward-pass dynamic programming approach is utilized to solve the stepwise fitting problem. Compared with the commercial solver, the dynamic programming approach has a distinct advantage in terms of computational efficiency due to its polynomial-order computational complexity.
(3) Multiarea DRPO considering practical regulation constraints of devices is solved in a fully decentralized manner using a three-stage decentralized method, preserving the dispatch independence and privacy of the distributed subnetworks. This solution method does not require a central coordinator, involves only minor boundary information exchange between the subproblems, and can effectively handle the discrete variables.

The remainder of this paper is organized as follows. The multiarea DRPO problem considering the practical regulation constraints of devices is formulated in Section 2. Section 3 presents the decentralized continuous RPO algorithm based on the standard OCD and three-stage decentralized DRPO algorithms in detail. Numerical tests are conducted to demonstrate the performance of the method in Section 4. Conclusions are finally drawn in Section 5.

2. Formulation of multiarea DRPO problem

In this section, the model for the multiarea DRPO problem considering the practical regulation constraints of devices is described. For clarity, the formulation of the multiarea DRPO problem can first be expressed in the following abstract form:

$$\begin{cases} \min & \sum\limits_{a\in\Gamma^{\text{area}}} f_a(\boldsymbol{x}_a, \boldsymbol{z}_a) \\ \text{s.t.} & \boldsymbol{g}_a(\boldsymbol{x}_a, \boldsymbol{z}_a) \leqslant 0 \quad \forall\, a \in \Gamma^{\text{area}} \\ & \boldsymbol{h}(\boldsymbol{x}_1,\ldots,\boldsymbol{x}_N, \boldsymbol{z}_1,\ldots,\boldsymbol{z}_N) \leqslant 0 \end{cases} \tag{1}$$

where $f_a(\cdot)$ and $\boldsymbol{g}_a(\cdot)$ represent the objective function and the constraints of area a, respectively. $\boldsymbol{x}_a$ and $\boldsymbol{z}_a$ represent the continuous and discrete variables of area a ($a = 1...N$), respectively. $\boldsymbol{h}(\cdot)$ represents the area-coupling constraints. Readers are referred to Tables A.6, A.7 and A.8 in Appendix A for the definitions of the symbols.

To classify the constraints as area-independent and area-coupling constraints, the structure of a multiarea power system is first described. A simple example is presented in Fig. 1, where the two areas are connected via a tie line at boundary buses i and j. Note that the decomposition can be generalized to power systems with more than two areas. Buses i' and j' denote virtual buses, and the parameters of branches ij' and ji' are identical to those of the tie line ij. Buses i and j' are regarded as the boundary buses of area a ($i \in \Gamma_a^{\text{BB}}, j' \in \Gamma_a'^{\text{BB}}$). In addition, the voltage magnitudes and phase angles of the boundary buses are defined as the boundary variables in this paper.

DRPO aims to minimize the total transmission loss over multiple periods while respecting the power balance constraints, voltage magnitudes and branch flow within their reasonable ranges. Moreover, the practical regulation constraints of the devices, including the constraints of maximum allowable regulation times, minimum regulation time interval and minimum regulation threshold, are involved. In this paper, the continuous decision variables of the multiarea DRPO model include the active and reactive power outputs of generators, voltage magnitudes and phase angles of buses:

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