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Two-phase mixed integer programming for non-convex economic dispatch problem with spinning reserve constraints

Z.L. Wu [a], J.Y. Ding [b], Q.H. Wu [a,c], Z.X. Jing [a,*], X.X. Zhou [d]

[a] School of Electric Power Engineering, South China University of Technology, Guangzhou 510640, China
[b] Guangdong Yudean Group Co. Ltd., Guangzhou 510630, China
[c] Department of Electrical Engineering and Electronics, The University of Liverpool, Liverpool L69 3GJ, UK
[d] China Electric Power Research Institute, State Grid Corporation of China, Qinghe, Beijing 100192, China

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ABSTRACT

This paper proposes a deterministic two-phase mixed integer programming (TPMIP) approach to solve the non-convex economic dispatch (ED) problem considering ramp rate constraints, valve-point effect (VPE), prohibited operating zones (POZs), transmission loss, and spinning reserve constraints. In the first phase, the non-smooth cost function induced by VPE is piecewise linearized and the POZs constraints are formulated as a set of mathematical formulas via a mixed integer encoding technique. Then, the non-convex ED problem is converted to a mixed integer programming (MIP) problem and can be solved by commercial optimization solvers. In the second phase, based on the solution obtained in the first phase, the range of the power output of each unit is compressed and then solve the MIP problem again to make a further exploitation for an optimal solution in the subspace of the whole solution domain. To demonstrate the effectiveness of TPMIP, it is applied to eight test systems and the simulation results are compared with those obtained by the existing methods cited in this paper. Numerical simulations have verified that the proposed method provides a comprehensive framework in solving the non-convex ED problem.

1. Introduction

Economic dispatch (ED) problem is a critical issue in power system operation and control as it provides guidance for the economic operation. The ED problem aims at determining an optimal power output schedule of the committed units so as to minimize the total cost of all committed units, while satisfying the operating constraints and the demand.

Many methods have been proposed to solve the ED problem, including mixed integer quadratic programming (MIQP) [1], semidefinite programming (SDP) [2], nonlinear programming (NLP) [3], and other gradient-based methods [4], which require a quadratic cost function of each unit. However, in practice, wire drawing effects occur when each steam admission valve in a turbine starts to open and thereby have a rippling impact on the unit input-output curve. This phenomenon is described as valve-point effect (VPE) and it is often represented by a sinusoidal term on the cost function. The inclusion of VPE makes the modeling of the fuel cost function of the units more practical and accurate. In order to consider the accurate cost function of each unit, the valve-point effect (VPE) should be taken into account in the realistic ED model. Due to the valve-point effect, the input-output curve of modern units inherently exhibits the non-linear and non-smooth characteristics [5]. In addition, vibrations may occur in a shaft bearing and can be amplified while operating in certain regions [6]. Consequently, the whole operating range of some units is not always available. As a result, most of the gradient-based methods, which require continuously differentiable cost functions and convex solution space, are inapplicable to the ED problem with valve-point effect (VPE) and prohibited operating zones (POZs).

Dynamic programming (DP) [7] imposes no additional requirements on the shape of the cost curve. However, with the dimensions increasing, DP can not avoid getting trapped into a local optimum and easily suffer from the curse of dimensionality. Reference [8] presents an innovative distributed auction-based algorithm (AA) to handle different types of non-convex ED problems. One of the very few gradient-based methods considering VPE is the Maclaurin series based Lagrangian method (MSL) [9], in which the sinusoidal term is represented by Maclaurin series and then solved by the Lagrangian method. Nevertheless, simulation results show that the exploitation capability of AA and MSL still needs improvement.

Compared with the gradient-based methods, the meta-heuristic methods have no restrictions on the shape of the cost function and

* Corresponding author.

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have a strong exploration capability in searching the non-convex solution space. Many meta-heuristic methods have been successfully applied to the non-convex ED problem, including genetic algorithm (GA) [5,6,10,11], particle swarm optimization (PSO) [12–16], evolutionary programming (EP) [17], differential evolution (DE) [18], firefly algorithm (FA) [19], tabu search algorithm (TS) [20], harmony search algorithm (HS) [21], clonal algorithm (AIS) [22], etc. To strengthen the exploitation capability, different strategies are integrated into the meta-heuristic method to form a hybrid method. In most of the hybrid methods, they often include two phases. The first phase is to find a desirable region in the solution space by using a meta-heuristic method and the second phase is to refine the solution by another method. These hybrid methods, which take advantages of both probabilistic and deterministic characteristics, have been proved to be effective in solving the non-convex ED problem, such as evolutionary programming combined with sequential quadratic programming (EP-SQP) [23], particle swarm optimization with sequential quadratic programming (PSO-SQP) [24], new particle swarm optimization with local random search (NPSO-LRS) [25], the hybrid algorithm consisting of genetic algorithm, pattern search and sequential quadratic programming (GA-PS-PSO) [26], a fuzzy adaptive particle swarm optimization algorithm with Nelder-Mead (NM) simplex search (FAPSO-NM) [27], etc. However, both the meta-heuristic and hybrid methods often need to specify many problem-based parameters and control parameters of the algorithm. Their main drawback is lack of guarantee of convergence to a stable solution in finite time and thereby they need to make stochastic analyses of the results [1]. Besides, the spinning reserve constraints are not under consideration in most of the above methods, which may lead to the instability of power system when a great fluctuation of the demand or a sudden failure in a certain large capacity unit occurs. Thus, the spinning reserve requirement should be embedded into the realistic ED model [28,29].

In this paper, a deterministic two-phase mixed integer programming (TPMIP) approach, which is based on linear approximation and mixed integer encoding technique, is proposed to solve the non-convex ED problem and the major characteristics of the proposed TPMIP method are as follows:

- Four practical constraints, including spinning reserve constraints, valve-point effect, prohibited operating zones, and transmission loss, are considered in the non-convex realistic ED model.
- The proposed method uses the linear approximation and the mixed integer encoding technique to convert the non-convex ED problem into a mixed integer programming (MIP) problem, and then the resulting problem can be solved by the commercial solvers.
- A novel two-phase mechanism is firstly presented to expedite the computational efficiency of the proposed TPMIP method.

The rest of this paper is organized as follows: (1) In Section 2, the mathematical formulation of the non-convex ED problem is presented. (2) In Section 3, TPMIP is proposed in detail. (3) In Section 4, TPMIP is implemented on eight test systems. (4) In Section 5, the conclusion of this paper is outlined.

2. Mathematical formulation of economic dispatch problem

2.1. Objective function

When VPE is not considered, the cost function of each unit is formulated as a second-order polynomial. The objective of the ED problem is to minimize the total cost as follows:

$$\min \quad F_T = \sum_{i=1}^{n} F_i(P_i) \qquad (1)$$
$$\text{where} \quad F_i(P_i) = a_i P_i^2 + b_i P_i + c_i$$

When VPE is considered, the cost function of unit i can be expressed as follows:

$$F_i(P_i) = a_i P_i^2 + b_i P_i + c_i + |e_i \sin(f_i(P_{i,\min} - P_i))| \qquad (2)$$

where F_T is the total cost; F_i is the cost function of unit i; a_i, b_i, c_i, e_i, and f_i are the cost coefficients of unit i; P_i is the power output of unit i; n is the total number of units.

2.2. Equality and inequality constraints

2.2.1. Power balance equation

The total power output should be equal to the demand plus the transmission loss. Therefore, the power balance equation should be as follows:

$$\sum_{i=1}^{n} P_i = P_{\text{load}} + P_{\text{loss}} \qquad (3)$$

where P_{load} is the demand and P_{loss} is the transmission loss. Based on the Kron's loss formula, P_{loss} can be represented as a function of the power outputs combined with the B coefficients as follows:

$$P_{\text{loss}} = \sum_{i=1}^{n}\sum_{j=1}^{n} P_i B_{ij} P_j + \sum_{i=1}^{n} B_{i0} P_i + B_{00} \qquad (4)$$

where the B coefficients, including B_{ij}, B_{i0}, and B_{00}, are used to calculate the transmission loss [4]. B_{ij} is a coefficient associated with P_i and P_j. B_{i0} is only associated with the power output of unit i and B_{00} denotes a constant.

2.2.2. Power output constraints

The power output of each unit has its lower bound and upper bound as follows:

$$P_{i,\min} \le P_i \le P_{i,\max} \qquad (5)$$

where $P_{i,\min}$ and $P_{i,\max}$ are the minimum and maximum power outputs of unit i, respectively.

2.2.3. Ramp rate constraints

The power output of unit i is affected by its ramp rate constraints as follows:

$$-\text{DR}_i \le P_i - P_i^0 \le \text{UR}_i \qquad (6)$$

where P_i^0 is the previous power output of unit i. DR_i and UR_i are the down and up ramp rate limits of unit i, respectively.

When (5) and (6) are considered at the same time, they can be rewritten as follows:

$$\max\{P_i^0 - \text{DR}_i, P_{i,\min}\} \le P_i \le \min\{P_i^0 + \text{UR}_i, P_{i,\max}\} \qquad (7)$$

2.2.4. Prohibited operating zones constraints

In practice, due to physical operation limitations, some units may have certain prohibited operating zones. The POZs constraints can be represented as follows:

$$P_i \in \begin{cases} P_{i,1}^a \le P_i \le P_{i,1}^b & \text{or} \\ P_{i,k}^a \le P_i \le P_{i,k}^b & \text{or} \\ \cdots & \\ P_{i,m_i}^a \le P_i \le P_{i,m_i}^b & \end{cases}, \quad \begin{matrix} k = 1, 2, \ldots, m_i \\ i \in \Phi \end{matrix} \qquad (8)$$

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