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Emission, reserve and economic load dispatch problem with non-smooth and non-convex cost functions using the hybrid bacterial foraging-Nelder–Mead algorithm

Rahmat-Allah Hooshmand *, Moein Parastegari, Mohammad Javad Morshed

Department of Electrical Engineering, University of Isfahan, Isfahan, Iran

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A B S T R A C T

In this paper, a new approach is proposed to solve the economic load dispatch (ELD) problem. Power generation, spinning reserve and emission costs are simultaneously considered in the objective function of the proposed ELD problem. In this condition, if the valve-point effects of thermal units are considered in the proposed emission, reserve and economic load dispatch (ERELD) problem, a non-smooth and non-convex cost function will be obtained. Frequency deviation, minimum frequency limits and other practical constraints are also considered in this problem. For this purpose, ramp rate limit, transmission line losses, maximum emission limit for specific power plants or total power system, prohibited operating zones and frequency constraints are considered in the optimization problem. A hybrid method that combines the bacterial foraging (BF) algorithm with the Nelder–Mead (NM) method (called BF–NM algorithm) is used to solve the problem. In this study, the performance of the proposed BF–NM algorithm is compared with the performance of other classic (non-linear programming) and intelligent algorithms such as particle swarm optimization (PSO) as well as genetic algorithm (GA), differential evolution (DE) and BF algorithms. The simulation results show the advantages of the proposed method for reducing the total cost of the system.

1. Introduction

The economic load dispatch of power plants is one of the most important problems in power system operations. In this regard, the ELD minimizes the generation cost of power plants so that the generated power satisfies the load demand by considering practical system constraints [1–3]. This is an extremely important problem in restructured power systems.

Due to increasing sensitivity regarding power plant emissions, the ELD must be performed such that the environmental emissions of power plants are minimized [4]. Furthermore, during a specific period of time, the emission constraint is considered in [5–7] to solve the ELD problem. The prohibited power generation zone is another constraint that can be considered in the ELD problem [8–10]. In addition, economic dispatch can be solved by considering frequency constraints [1].

To develop a complete model of the ELD problem, the effect of the spinning reserve constraint [11–13] as well as the valve-point effect [14–21] and transmission line losses [22,24] can also be taken into account. In most studies, the generation cost function is considered to be quadratic function, but a cubic cost function more closely conforms to the generation cost [14]. Therefore, the use of a cubic cost function leads to more accurate modeling of power plant costs.

The ELD problem is an optimization problem; thus, a large number of methods are available to solve this problem. Recently, stochastic search algorithms such as PSO [16,23,25], GA [14], direct search [22], and DE algorithms [17] have been successfully used to solve the ELD problem. Each of these algorithms has its own advantages and disadvantages. For example, the direct search method and GA have slow execution speeds, and the PSO algorithm requires the execution of many repeated stages. The above -mentioned search methods determine the local optimal point but cannot find that optimal solution.

The BF algorithm is a new optimization algorithm that has recently been considered to solve the optimization problem [26]. It covers a wide search region but has low convergence speed. In this respect, a hybrid method combines BF algorithm and NM method (BF–NM algorithm) [27,28]. By combining these two methods, the search power of intelligent methods and the precision of conventional methods are simultaneously employed [27].

In this paper, a new ERELD problem is presented that is solved using the BF–NM algorithm for a system with 13 generation units by considering a cubic cost function and the valve-point effects. In

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* Corresponding author. Tel.: +98 311 7934073; fax: +98 311 7933071.
E-mail addresses: Hooshmand_r@eng.ui.ac.ir (R.-A. Hooshmand), Parastegari@eng.ui.ac.ir (M. Parastegari), MJ.Morshed@gmail.com (M.J. Morshed).

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addition, the transmission losses, maximum emission limit, and practical constraints of the power plants are considered in the problem. The frequency deviation, minimum frequency limit and maximum permissible environmental emission constraints are also used in the problem to improve power system security. The simulation results validate the performance and accuracy of the proposed method for solving the ERELD problem by placing practical constraints in power system in comparison with other optimization algorithms.

2. Problem formulation

The proposed ERELD problem consists of an objective function and practical constraints. The objective function and constraints are introduced in following subsections.

2.1. The problem objective functions

2.1.1. The fuel cost function of power plants

The total system fuel cost (F_{Cost}) is equal to the sum of the unit fuel costs, which is defined as follows:

$$F_{Cost} = F_1 + F_2 + F_3 + \ldots + F_n = \sum_{i=1}^{N} F_i(P_i) \tag{1}$$

where P_i and F_i are the output power and the generation cost of ith generating units and N is the number of power plants. The cost function is generally considered to be a square cost function [29,30]. However, a cubic cost function is more appropriate and accurate. So, the proposed total generation cost can be expressed as follows:

$$\min \quad F_{Cost} = \sum_{i=1}^{N} (a_i + b_iP_i + c_iP_i^2 + d_iP_i^3) \tag{2}$$

where a_i, b_i, c_i and d_i are the cost coefficients.

2.1.2. The valve-point effect

If the power output of a generator with multi-valve steam turbines is increased to meet the increased demand, various steam valves should to be opened in sequence. As shown in Fig. 1, the valve-point effect can be considered by adding the absolute value of a sinusoidal function with a cubic cost function [14–18]. Thus, the cost function is modified as follows:

$$\min \quad F_{Cost} = \sum_{i=1}^{N} \left[\left(a_i + b_iP_i + c_iP_i^2 + d_iP_i^3 \right) + \left| e_i \cdot \sin\left(f_i(P_{i,\min} - P_i) \right) \right| \right] \tag{3}$$

where e_i and f_i are the coefficients of the ith unit of valve-point effects on fuel cost.

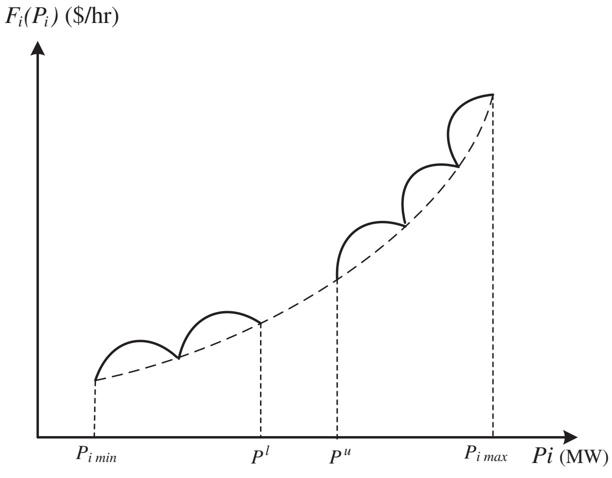

Fig. 1. A cost function of a unit with valve-point effect and prohibited operating zones.

2.1.3. Power plant spinning reserve cost function

Plants should have enough spinning reserve to provide energy without interruption for customers. This reserve provides cost for the system [12]. Thus,

$$FR_{Cost} = FR_1 + FR_2 + \ldots + FR_n = \sum_{i=1}^{N} FR_i(R_i) \tag{4}$$

where FR_{cost} is the total reserve cost of the whole system and R_i is the reserve for the ith unit.

The determination of spinning reserve values to minimize the FR_{cost} function is one of the main objectives in power system operations. Therefore,

$$\min \quad FR_{Cost} = \sum_{i=1}^{N} (a_{ri} + b_{ri}R_i + c_{ri}R_i^2) \tag{5}$$

where a_{ri}, b_{ri} and c_{ri} are the coefficients of the reserve cost of the ith generator.

2.1.4. Power plants emission function

Fossil-based generating stations are the main sources of nitrogen oxides (NO_x) and sulfur oxides (SO_x). Thus, the environmental protection agency strongly advises them to reduce their emissions. For this purpose, generators should pay a penalty for environmental emissions. Each generator emission is given as a function of its output as follows [4]:

$$\min \quad F_{Emission} = \sum_{i=1}^{N} (\alpha_i + \beta_iP_i + \gamma_iP_i^2) \tag{6}$$

where $F_{Emission}$ shows the total power plant emission function and α_i, β_i and γ_i are the ith power plant emission coefficients.

2.1.5. Price penalty factor method

There are several ways to include emission into the economic dispatch problem. One approach is to include the reduction of emission as an objective. A price penalty factor (Q_r) is another approach which can be used in the objective function to combine the fuel cost as $/h and emission functions as ton/h [7,32,33]. A price penalty factor (Q_r) is the ratio between the maximum fuel cost of thermal units and the maximum emission of the corresponding unit [33]. The factor of ith generator $Q_{r,i} = F_{Cost,i}(\max)/F_{emission,i}(\max)$ can be used for the conversion of the emission value at the scale of the generation cost function [32,33] and is computed as follows:

$$Q_{r,i} = \frac{F_{Cost,i}(\max)}{F_{emission,i}(\max)} = \frac{a_i + b_iP_{i,\max} + c_iP_{i,\max}^2 + d_iP_{i,\max}^3}{\alpha_i + \beta_iP_{i,\max} + \gamma_iP_{i,\max}^2} \tag{7}$$

2.1.6. The proposed objective function

Fuel, spinning reserve and emission costs are in conflict with each other. In other words, as the minimum generation and reserve costs and minimum emission do not occur at a single point, it is necessary to optimize them, simultaneously. Multi-objective optimization methods can be used to solve this optimization problem. To generate the non-inferior solutions of a multi-objective optimization problem, the weighting method can be used [7,31]. This approach aggregates all objective functions in a weighted combination, producing a single one [31]. Therefore, the ERELD