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Optimization of air quantity regulation in mine ventilation networks using the improved differential evolution algorithm and critical path method

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ABSTRACT

In mine ventilation networks, the reasonable airflow distribution is very important for the production safety and economy. Three basic problems of the natural, full-controlled and semi-controlled splitting were reviewed in the paper. Aiming at the high difficulty semi-controlled splitting problem, the general nonlinear multi-objectives optimization mathematical model with constraints was established based on the theory of mine ventilation networks. A new algorithm, which combined the improved differential evaluation and the critical path method (CPM) based on the multivariable separate solution strategy, was put forward to search for the global optimal solution more efficiently. In each step of evolution, the feasible solutions of air quantity distribution are firstly produced by the improved differential evolution algorithm, and then the optimal solutions of regulator pressure drop are obtained by the CPM. Through finite steps iterations, the optimal solution can be given. In this new algorithm, the population of feasible solutions were sorted and grouped for enhancing the global search ability and the individuals in general group were randomly initialized for keeping diversity. Meanwhile, the individual neighborhood in the fine group which may be closely to the optimal solutions were searched locally and slightly for achieving a balance between global searching and local searching, thus improving the convergence rate. The computer program was developed based on this method. Finally, the two ventilation networks with single-fan and multi-fans were solved. The results show that this algorithm has advantages of high effectiveness, fast convergence, good robustness and flexibility. This computer program could be used to solve large-scale generalized ventilation networks optimization problem in the future.

1. Introduction

The main function of mine ventilation is to dilute and exhaust hurtful gases, dusts, heat and humidity. Obviously, the effect of mine ventilation depends on air flow modes and air quantity distribution in the ventilation networks, which are changing with mining and tunneling. Therefore, the air-quantity regulation is necessary for meeting and maintaining the airflow demand in all workplaces. It is a frequent and important job of mine ventilation management to guarantee mine safety production.

While the air quantities of workplaces, air velocities of airways and mine ventilation total resistance are controlled within reasonable ranges, we try to seek an optimal regulation scheme which could minimize the total ventilation energy consumption and the sum of adjusted branches, in order to guarantee mine ventilation system to operate safely, reliably and economically. That is the optimization problem of air quantity regulation in mine ventilation networks. Mine ventilation networks are abstracted as strongly connected and oriented graphs when the general outlet and inlet nodes are connected by the return dummy branch. It is a complex problem to study the airflow distribution in mine ventilation networks. According to the number of fixed-quantity branches in ventilation networks, there are three kinds of problems as follows.

(1) The problem of the natural splitting in ventilation networks. In this problem, the air quantities of all branches can be determined while resistance factors of all branches and fan characteristics are known. This problem can be traditionally described as the system of nonlinear equations determined by Kirchhoff's first and second laws, and solved by the Hardy Cross algorithm or the Scott-Hinsely algorithm [1–4].

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(2) The problem of the full-controlled splitting in ventilation networks. Although air quantities and resistance factors for all branches are known, pressure drops of branches must be regulated in this problem because Kirchhoff's second law is not satisfied. If we assume that each airway branch is adjustable, then the total number of regulators equals that of branches. Because the number of linear fundamental loop equations determined by Kirchhoff's second law is less than that of regulators, the system of the equations has infinite solutions. If we add an objective function, such as the minimum power consumption of fans, this problem can be transformed into a linear optimization problem with constraints, and then the optimal solution of this problem can be obtained by the linear programming method [5], the critical-path method (CPM) [6] or the path method [7–10].

(3) The problem of the semi-controlled splitting in ventilation networks with fixed quantity and unfixed quantity branches. Here, the variables could include air quantity, regulator pressure loss and fan pressure for each branch. Just same as the second problem, variables are relatively more. There are three solving approaches as follow:

First, reduce the number of variables to balance the number of variables with the number of equations by predetermining the location and number of regulators. Newton method [11] could be used to solve the unique solution of the nonlinear equations without any objective function. The second is the so-called two steps method [12]: the air quantities of all branches are calculated by the natural splitting solution in the first step, and then, the optimal locations and pressure drops of the regulators can be determined by the same method as the full-controlled splitting solution. The results obtained by these two methods are not the global optimal solutions but only a feasible solution due to that the interaction between air quantity and regulator pressure loss are ignored. The third method is synchronously to solve all variables of the third problem. An objective function is introduced for changing this issue into a nonlinear optimization problem to obtain the finite solutions. Commonly, the objective function is defined as the total power consumptions of fans, meanwhile, constraints include both nonlinear equality constraints determined by Kirchhoff's laws and the inequality constraints consisted of the upper and lower limits of each variable. The traditional nonlinear programming methods can be used, such as the sequential unconstrained minimization techniques [13], the generalized reduced gradient method [14], the constrained variable metric method [15], and the internal penalty function method [16], etc. Although it is effective to solve the convex nonlinear optimization problem, these methods would be possible to cause premature convergence and the Maratos effect when these methods are applied in the large-scale non-convex nonlinear optimization problem [17]. Due to the existence of the diagonal branches with variable airflow direction, the feasible ranges of variables are enlarged and changed into non-convex discontinuity, thus it has a strong influence on the convergence and effectiveness of those optimization methods with calculating derivatives.

Evolutionary algorithm is popular among scholars because of its superiority in engineering optimization. This kind of algorithm is a stochastic population search method without calculating derivatives, which has many merits such as simple calculation, flexible and various search strategies, stronger applicability and easy program. Theoretically, only if the search strategy is appropriate, the global optimal solution can be obtained to a great extent.

As a representative of early evolutionary algorithm, genetic algorithm (GA) has been widely used to solve the nonlinear optimization problem of air quantity regulation for mine ventilation networks [18]. The standard GA uses binary coding to express real variables. The randomness of the coding mode reduces the local search ability for the high-dimensions problems, and the frequency of coding and decoding induces tedious calculation and reduces computational accuracy. However, the coding mode could accomplish the operators of crossover, mutation and selection easily. In order to avoid the deficiencies mentioned above, differential evaluation algorithm (DE) was proposed by Storn and Price [19–21]. Compared with the GA, DE, which is essentially a greed GA with the idea of retaining good individual based on real coding, satisfies certain constraint conditions easily and has the stronger local-search ability. However, deficiencies such as large calculation, premature and slow convergence rate for a large-scale non-convex optimization problem still exist.

Therefore, it is very necessary to explore a fast and effective method of obtaining the global optimal solutions of airflow regulation in mine ventilation networks. What's more, it can provide better technical supports for the intelligent control of mine ventilation systems.

2. Model of optimizing air quantity regulation in mine ventilation networks

In general, airflow regulation optimization in mine ventilation networks is described as a minimization model, whose objective function is the minimum number of regulators and ventilation energy consumption. Considering that every ventilation network graph can be separated into two sets: a spanning tree and its chords. All variables consist of the unknown air-quantities of branches and pressure drops of regulators in the ventilation network. The independent variables are the air quantities of the non-fixed chords, and the others are dependent variables. The constraints includes that the upper and lower bounds of all variables which are determined by Coal Mine Safety Rules. Besides, airflow parameters obey the Kirchhoff's laws of ventilation networks and the square law for pressure drop. For any given mine ventilation network, the generalized mathematical model of air quantity regulation optimization (ARO) is expressed in Eqs. (1)–(4).

The objective function can be described as:

$$\min f = w_1 \sum_{i=1}^{N} \frac{h_{F_i} q_{F_i} - P_{F_i \min}}{P_{F_i \max} - P_{F_i \min}} + w_2 \left(\sum_{\substack{j=1 \\ \Delta h_j > 0}}^{b} \frac{1}{m - N} \right) \tag{1}$$

The constraint conditions can be expressed as follows:

(1) Air quantity equations of nodes are determined by Kirchhoff's first law, as shown in Eq. (2).

$$q_j = \sum_{i=1}^{l} C_{ij} q_{Y_i} + \sum_{i=l+1}^{m} C_{ij} q_{Y_i}, j = 1, 2, \cdots, b \tag{2}$$

(2) Air pressure equations of meshes are determined by Kirchhoff's second law, as shown in Eq. (3).

$$\sum_{j=1}^{b} C_{ij} \left(r_j q_j^2 + \Delta h_j - h_{F_i} - h_{Z_j} \right) = 0, i = 1, 2, \cdots, m \tag{3}$$

(3) Upper and lower bounds of variables are as follows:

$$\begin{cases} q_{j\min} \leqslant |q_j| \leqslant q_{j\max} & \text{for the allowed reverse branches} \\ q_{j\min} \leqslant q_j \leqslant q_{j\max} & \text{for the prohibited reverse branches} \\ 0 \leqslant \Delta h_j \leqslant \max\limits_{1 \leqslant i \leqslant N} \{ h_{F_i \max} \} \\ h_{F_i \min} \leqslant h_{F_i} \leqslant h_{F_i \max}, i = 1, 2, \cdots, N \end{cases} \tag{4}$$