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Research on Control Optimization Method of Mine Ventilation System Based on Intelligent Optimization Algorithm

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Abstract. In view of the complex ventilation network in the mine, many influencing factors, and the complex establishment of the air demand model, this paper establishes an air volume optimization model with the minimum energy consumption of the entire ventilation network as the optimization objective, and adds the air volume balance law conditions, the air pressure balance law conditions, the branch air demand law conditions, the air resistance regulation law conditions, and the fan conditions as constraints to the model. Then, the intelligent algorithm is used to solve the problem. In order to make the intelligent algorithm converge faster and solve the problem optimally, the Grey Wolf algorithm is improved. Finally, the model and the improved intelligent algorithm are used to optimize the ventilation regulation of the actual operating coal mine, and the air volume control scheme is given.

Keywords: mine ventilation system, air volume regulation model, Intelligent optimization algorithm, Improved Grey Wolf algorithm

1 Introduction

According to the requirements of relevant laws and regulations, reliable mine ventilation system must be used to ensure the safe production of the coal mine. The mine ventilation system uses natural air pressure and ventilator to transport fresh air to various air consumption sites, and dilutes toxic and harmful gases and turbid air in time and discharges them out of the well to ensure the life safety of underground operators. However, in actual production, the mine ventilation system has many branches and the ventilation network is staggered, which makes the daily management and air volume regulation of the mine more complex. Therefore, how to meet the air consumption of each air consumption point in the complex ventilation network system and realize the reasonable and optimized control of the air consumption has become the focus of the current mine ventilation system research.

In this paper, taking mine B of A Group in Tangshan as an example, an optimization model is established based on the ventilation network, and the improved Grey Wolf algorithm is used to solve the problem. The completed work is as follows:

(1) According to the constraint conditions in actual production, the mathematical model of air volume optimization close to the real environment is established;

(2) When solving the model, the improved Grey Wolf algorithm is used. The improved Grey Wolf algorithm achieves faster convergence speed and avoids the improvement of local optimal solution;

(3) According to the algorithm, this paper gives the air volume adjustment scheme for all network branches of the target mine.

The structure of this paper is arranged as follows. In Chapter 2, the research results of relevant scholars are searched and the research ideas of this paper are determined by comparison. In Chapter 3, the main factors related to ventilation in the current mine production are analyzed, and the mathematical model of air volume optimiza-

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tion is established. In Chapter 4, in order to solve the optimal solution of the model, the Grey Wolf algorithm is improved to avoid the slow convergence speed of the algorithm and the problem of falling into the local optimal solution, The fifth chapter optimizes the air volume adjustment for the actual ventilation branch of Tangshan A Group B Mine, and obtains the best air volume adjustment scheme. The sixth chapter summarizes the contents of this paper and proposes further research directions.

2 Related Work

In recent years, scholars at home and abroad have studied the optimization theory of ventilation network and the intelligent control strategy of air volume. W. Nyaaba, proposed a method to model the mine ventilation network as a nonlinear model, and discussed the use of first-order Lagrange formula as a solution method, which simplified the complexity of calculation [1]. M. Bascompta, concerned that the problem of wind speed exceeding the limit in the roadway will seriously affect the airflow stability and safe production of the roadway, analyzed the key causes of the ventilation problem in the case study of the coal mine, and proposed a solution using the analysis method [2]. Kolobe designed a sufficiently robust ventilation control system according to the dynamic gas flow changes of Henderson mine ventilation system to ensure the dynamic optimization and regulation of the ventilation system. These changes in demand are caused by the transition from one panel to another, as well as changes in design and production requirements [3]. Xinming Lu, starting with the topological structure and state equation of the air network, deeply discussed the theoretical doubtful points of the natural air distribution algorithm, the on-demand air distribution calculation and the optimization of the wind resistance adjustment one by one, and conducted in-depth research on the key technologies such as the advance prediction of the air demand, the identification of the reverse air duct, the reliability adjustment optimization, the initialization of the ventilation system, the fault diagnosis of the ventilation system, the intelligent control of the doors and windows, and the intelligent ventilation software system [4]. Xiaodong Pei, aiming at the current situation of frequent changes in the branch air demand of the ventilation system, established a regulation model combining the branch air resistance regulation and the fan frequency conversion regulation, and established a cellular automata model in the ventilation network. The verified air demand was substituted into the air network for iterative calculation, and the adjusted air resistance of the associated branch was inversely calculated, and the expected regulation results were verified in advance through the air network calculation [5]. Shuxian Su designed an intelligent ventilation management system for coal mine based on rough set algorithm and improved capsule network. The system adopts the information reduction model based on rough set, the capsule perception model of coal mine ventilation environment based on improved capsule network, and reconstructs the capsule neuron group through convolution to collect and optimize the data features [6]. Jialin Song, taking the lowest total power consumption of the ventilation network as the objective function and the basic law of the mine ventilation network as the constraint conditions, established a nonlinear unconstrained optimization model of the ventilation network, and adopted the method of combining improved particle swarm optimization algorithm and tabu search algorithm to improve the convergence speed and accuracy of the algorithm [7]. Xinzhong Wu established a nonlinear optimization mathematical model of the ventilation network with the goal of maximizing the adjustable branch air volume of the mine ventilation network. Aiming at the constraints such as air volume balance and air pressure balance in the optimization model, he solved the problem by calculating the sensitivity matrix of the ventilation network, and realized the search for the optimal result based on the differential grey wolf algorithm [8].

3 Establishment of Ventilation Network Model

Energy conservation and emission reduction is the current global production goal. The mathematical model of ventilation network optimization for the purpose of energy conservation is a nonlinear non-convex programming problem. Therefore, this paper establishes a ventilation network model according to the laws to be satisfied under the ventilation environment [9].

3.1 Establishment of Constraints

With the minimum energy consumption of the entire ventilation network as the optimization objective, the mathematical model is constrained by the law of air volume balance, the law of air pressure balance, the law of branch air demand, the law of wind resistance adjustment, and the fan conditions.

(1) Constraints of air volume balance law

When the air flows freely in the whole ventilation network in an ideal state, the air volume of each branch in the network meets the node air volume balance law and the loop medium pressure balance law, and the air volume of each branch is expressed as A, so the air volume balance condition of each node in the network is:

$$\sum_{j=1}^{n} b_{ij} q_j = 0(i = 1, 2, \cdots, m-1). \tag{1}$$

Where, A is the element in the incidence matrix, and B is the air volume of each branch of the network.

$$b_{ij} = \begin{cases} 1, & \text{The air flow of the jth branch flows into the ith node} \\ -1, & \text{The air flow of the jth branch flows out of the ith node} \\ 0, & \text{Node is not the endpoint of the branch} \end{cases}. \tag{2}$$

(2) Constraints of wind pressure balance law

According to the law of wind pressure balance, the clockwise wind pressure of the closed circuit is equal to the counterclockwise wind pressure, so the wind pressure balance condition is expressed as:

$$\sum_{j=1}^{n} L_{ij} r_j q_j \left| q_j \right| - h_{fi} - h_{ni} = 0, (i = 1, 2, \cdots, b). \tag{3}$$

In the formula, L_{ij} is the element in the basic directed path matrix, r_j is the wind resistance of each branch. For on-demand ventilation, the air demand of each branch can not be met by natural wind alone, so the pressure regulation module is added in the formula to make the air pressure reach balance, so the updated formula is:

$$\sum_{j=1}^{n} L_{ij} r_j q_j \left| q_j \right| - h_{fi} - h_{ni} + \Delta h_i = 0, (i = 1, 2, \cdots, b). \tag{4}$$

The pressure regulation module can be described in detail using the following formula:

$$\Delta h_i = \sum_{j=1}^{n} L_{ij} s_j q_j \left| q_j \right|, (i = 1, 2, \cdots, b). \tag{5}$$

Therefore, the formula of wind pressure balance conditions is finally summarized as follows:

$$\sum_{j=1}^{n} L_{ij} (r_j + s_j) q_j \left| q_j \right| - h_{fi} - h_{ni} = 0, (i = 1, 2, \cdots, b). \tag{6}$$

(3) Air demand constraints

From the perspective of relevant safety production specifications and practical applications, the air demand of each air demand branch is not a fixed value, but varies within a range according to the actual situation. Therefore, the air demand of each air demand branch is established as an interval function:

$$l_{q_j} \le q_j \le \mu q_j \quad (j \in NK). \tag{7}$$

Where, l_{q_j} represents the lower limit of the air demand, $l_{q_j} = 4 \times N$ is generally set, N represents the maximum number of workers in each roadway, μq_j represents the upper limit of the air demand, the upper limit depends on the maximum capacity of the fan, and NK represents the collection of the air demand branches.

(4) Adjustable drag constraints

According to the specific use, the purpose of each branch and the position difference in the ventilation network, some can be adjusted by increasing resistance, some can be adjusted by reducing resistance, and some cannot be adjusted. Therefore, the basic conditions for the regulation of network ventilation are expressed as follows:

$$ls_j \le s_j \le \mu s_j \quad (j = 1, 2, \cdots, n) . \tag{8}$$

Where, ls_j is the lower limit of the allowable adjustment of the wind resistance in the branch, μs_j is the lower limit of the allowable adjustment of the wind resistance in the branch, $ls_j = \mu s_j = 0$ is the branch is not allowed to adjust, $ls_j = 0, \mu s_j > 0$ is only allowed to increase the resistance, $ls_j < 0, \mu s_j > 0$ is allowed to increase the resistance and reduce the resistance, and $ls_j < 0, \mu s_j = 0$ is only allowed to reduce the resistance.

(5) Fan constraints

The main sources of mine stroke are natural air and fan supply, and the natural air volume is limited, which is generally difficult to meet the production demand. Therefore, the mine mainly relies on the fan for air supply. According to the principle of the fan, the upper and lower limits of the fan's air volume are determined by the fan's characteristic curve:

$$lh_{fi} \le h_{fi} \le \mu h_{fi} \quad (i = 1, 2, \cdots, f) . \tag{9}$$

Where, lh_{fi} represents the lower limit of the fan supply air volume, and μh_{fi} represents the upper limit of the fan supply air volume.

3.2 Establishment of Objective Function

This paper takes the minimum energy consumption as the objective function, and the minimum energy consumption can use the minimum output power of the fan and the minimum total energy consumption of the network to establish a function model:

$$\min Z = \sum_{i=1}^{f} h_{fi} q_{fi} . \tag{10}$$

Or expressed as:

$$\min Z = \sum_{j=1}^{n} (r_j + s_j) q_j^3 . \tag{11}$$

Where, f is the number of fans, and q_{fi} is the air volume of the ith fan.

3.3 Optimization Model

Selecting a reasonable working point of the fan requires that the static pressure efficiency of the fan should not be less than 70% economically, and that the fan should not surge in safety. It is stipulated that the actual working air pressure of the fan should not be higher than 90% of the rated air pressure [10]. Therefore, the above air volume balance law constraints, air pressure balance law constraints, branch air demand constraints, branch regulation wind resistance constraints, fan air volume constraints and minimum energy consumption are taken as the objective functions. The mathematical model is expressed as follows:

$$\min W = f_{\min} (\sum_{j=1}^{n} [(r_j + s_j) q_j^3 + L_{ij} (r_j + s_j) + q_j + s_j + h_{fi}) + P(\sigma_k, x) . \tag{12}$$

Where, $P(\sigma_k, x)$ is the penalty function and σ_k is the penalty factor. According to the actual production situation, the specific finite value of the penalty factor σ_k can be obtained, which can effectively solve the problem of internal and external penalty functions.

4 Improved Grey Wolf Algorithm

Grey wolf optimization algorithm (GWO) is a swarm intelligence optimization algorithm evolved from the hunting behavior of wolves and the strict hierarchy of wolves [11]. The implementation process of the algorithm is as follows:

(1) Wolf hierarchy

There is a strict social hierarchy among wolves, for example, the social hierarchy between the head wolf and the common wolf is very clear. When using the algorithm, we divide the wolf pack into four levels, namely α, β, δ, ω, and gradually decrease from top to bottom, as shown in Fig. 1. The main idea of the algorithm is that the optimization process of the whole wolf pack is initiated by the lowest level ω wolf, and the task assigned by the high-level wolf is completed, and the position close to the prey is constantly searched. Wolf α is the head wolf of the whole wolf pack, giving orders, and Wolf β and δ are responsible for coordinating the work of Wolf α.

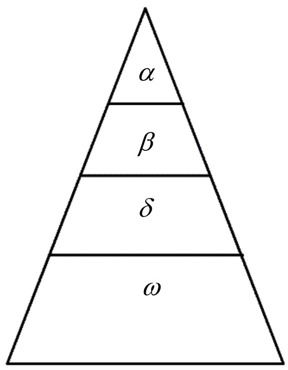

Fig. 1. Wolf pack level

(2) Wolf hunting

The whole optimization process of the algorithm searches for prey by tracking and surrounding approximation. The formula for updating the population position in the surrounding phase is as follows:

$$D = \left| C X_P(t) - X(t) \right| . \quad \textbf{(13)}$$

$$X(t+1) = X_P(t) - A \cdot D . \quad \textbf{(14)}$$

Where, D represents the distance between the wolves and the target prey, t represents the number of iterations of the algorithm, $X_P(t)$ and $X(t)$ represent the position of the prey after the t iteration and the current position of the search individual, and A and C are the control parameters.

$$a(t) = 2(1 - t / T_{\max}) . \quad \textbf{(15)}$$

$$A = 2ar_1 - a, C = 2r_2 . \quad \textbf{(16)}$$

Among them, $T_{\max}$ is the maximum number of iterations, parameter a is reduced from 2 to 0 during the iteration process, r_1 and r_2 are random values, $0 \le r_1$, $r_2 \le 1$, and the other three levels of wolves are responsible for locating the prey position in the attack stage, and guiding the search individual ω to complete the behavior of approaching the siege, etc. The process representation method is as follows:

$$\begin{cases} D_a = \left| C_1 \cdot X_a - X \right| \\ D_\beta = \left| C_2 \cdot X_\beta - X \right| \\ D_\delta = \left| C_3 \cdot X_\delta - X \right| \end{cases}. \tag{17}$$

$$\begin{cases} X_1 = X_a - A_1 \cdot D_a \\ X_2 = X_\beta - A_2 \cdot D_\beta \\ X_3 = X_\delta - A_3 \cdot D_\delta \end{cases}. \tag{18}$$

$$X(t+1) = \frac{X_1 + X_2 + X_3}{3}. \tag{19}$$

Where, D_α , D_β , D_δ are the distances between α , , and search individual ω , X_1, X_2, X_3 are the positions of search individual ω to move next after being guided by α , β , δ . $X_\alpha, X_\beta, X_\delta$ are the positions of individuals α , β , δ from the prey after the tth iteration, X is the current position of search individual, A_1 and C_1 are the control parameters corresponding to gray wolf individual α , A_2 and C_2 are the control parameters corresponding to gray wolf individual β , A_3 and C_3 are the control parameters corresponding to gray wolf individual δ .

4.1 Grey Wolf Algorithm Improvement Process

In the process of searching for the optimal solution, the gray wolf algorithm has low search efficiency, and its accuracy needs to be improved, which is easy to fall into local optimum. Therefore, according to the actual situation of ventilation network and the defects of Grey Wolf algorithm, this paper proposes an improved method to improve the efficiency of optimization. In this paper, DE algorithm [12] is introduced to improve the Grey Wolf algorithm by virtue of its excellent global optimization advantages.

(1) Algorithm mutation

In order to achieve the best global search performance of DE algorithm, perform $DE/rand/1$ mutation operation on the algorithm, and the operation process is as follows:

$$V_{i,g} = X_{a,g} + F_r \times (X_{b,g} - X_{c,g}). \tag{20}$$

Where, $V_{i,g}$ is the individual position after mutation, $X_{a,g}, X_{b,g}, X_{c,g}$ are the individual positions randomly selected from the current population, and F_r is the scaling factor, which is used to control the variable scaling deviation, and the range is $F_r \in [0,1]$.

(2) Increase population diversity

In order to improve the accuracy of the algorithm search, we need to operate on the diversity of the population. In this paper, we use the binomial method to achieve the sample diversity operation.

$$U_{i,g+1} = \begin{cases} V_{i,g}^J, (rand^J(0,1) \le C_r) or (J = j_{rand}) \\ X_{i,g}^J, otherwise \end{cases}. \tag{21}$$

Where, $U_{i,g+1}$ is the individual position after two operations, $C_r \in [0,1]$ is the operation probability, J is the current dimension, and j_{rand} is the randomly selected dimension.

(3) Select method

In this paper, greedy algorithm is used for selection. The idea of greedy algorithm is to compare the new offspring and the parent, and then enter the better one into the next population, thus ensuring the positive evolution of the population [13]. The selection expression is:

$$X_{i,g+1} = \begin{cases} U_{i,g+1} & if, f(U_{i,g+1}) < f(X_{i,g}) \\ X_{i,g} & otherwise \end{cases}. \tag{22}$$

4.2 Improved Grey Wolf Algorithm Optimization Process

Combining Grey Wolf algorithm with DE algorithm, the improved algorithm can overcome the shortcomings of Grey Wolf algorithm such as low computational efficiency and easy to fall into local optimal solution.

The pseudocode of the algorithm is as Table 1:

Table 1. The pseudo code of the algorithm

Algorithm 1. Optimization algorithm
1: Set:
Population size;
Optimization dimension;
Cross probability;
Scale factor range;
2: Initialization:
Primary population;
Parent population;
Mutant population;
3: Input:
Individual fitness function value of parent population;
The objective function is optimal;
The objective function is suboptimal;
The objective function is more suboptimal;
4: if ($t \le T_{\max}$)
while do
updated $X_\alpha, X_\beta, X_\delta$;
else if ($t = T_{\max}$ or all individuals converge)
end if
5: Output:
Control parameters A, C and a are calculated by formula (15) (16);
The search individual is calculated by formula (17) (18) (19);
The distance between three characters $X_\alpha, X_\beta, X_\delta$;
The new position of the current individual;
New parent population;
Individual fitness of population;
The individual fitness of the new progeny population and the new progeny population is calculated by formula (20) (21);
The optimal individuals in the offspring population and the parent population are calculated from (22);
6: End

5 Experimental Results and Analysis

Use Matlab software to conduct data modeling, and use the improved Grey Wolf algorithm to optimize the mine ventilation optimization algorithm. This paper takes Tangshan A Group B Coal Mine as an example and devotes to simulation analysis. The coal mine is supplied with air from the main shaft and auxiliary shaft, and the return air shaft is supplied with air. The ventilation mode is mainly fan extraction ventilation. The fan model is GAF33.5-16-2. There are two sets in total, one for operation and one for standby. The topology of the air duct network in the shaft is shown in Fig. 2.

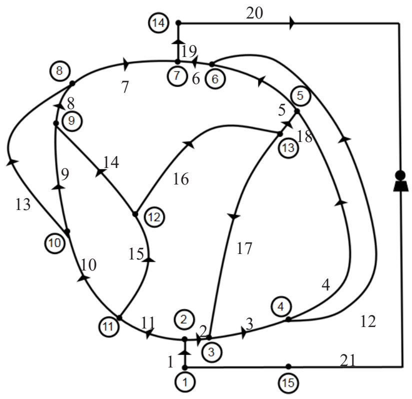

Fig. 2. Topology diagram of ventilation network structure

The initial ventilation data of the ventilation network is shown in Table 2:

Table 2. Initial ventilation volume in ventilation network

Branch number	Start node	Air volume/($m^3 \cdot s^{-1}$)	Can it be adjusted
1	11	44.86	No
2	22	19.82	No
3	33	11.32	Yes
4	44	9.03	Yes
5	55	14.67	Yes
6	66	24.02	Yes
7	77	19.21	Yes
8	88	5.46	Yes
9	99	6.42	Yes
10	1010	14.81	Yes
11	1111	22.83	No
12	44	8.98	Yes
13	1010	7.06	Yes
14	1212	6.02	Yes
15	1111	9.21	Yes
16	1212	3.82	Yes
17	1313	1.55	Yes
18	44	9.28	Yes
19	77	44.86	No
20	1414	44.86	No
21	1515	44.86	No

5.1 Initial Parameter Setting

In this paper, the air volume of the 8th branch circuit is adjusted, and the improved algorithm described in this paper is used to optimize and find the optimal solution. First, set the parameters, set the population size as $N = 50$, the optimization variable dimension as $d = 2$, the maximum number of evolution iterations as $T_{\max} = 200$, and the crossover probability as $C_r = 0.2$. In order to illustrate the effectiveness of the algorithm and avoid contingency, genetic algorithm (GA) and particle swarm optimization (PSO) are selected for comparison. The comparison results are shown in Table 3. The optimization effect of different algorithms on the 8th branch route of this paper is shown in Fig. 3.

Table 3. Algorithm comparison results

Performance parameter	Algorithm in this paper	GA	PSO
Average value of air volume optimization / ($m^3 \cdot s^{-1}$)	8.52	8.35	8.21
Optimal solution of air volume optimization / ($m^3 \cdot s^{-1}$)	8.57	8.36	8.23
Mean convergent algebra / frequency	96	88	67
Average running time / s	16.8	17.4	16.5

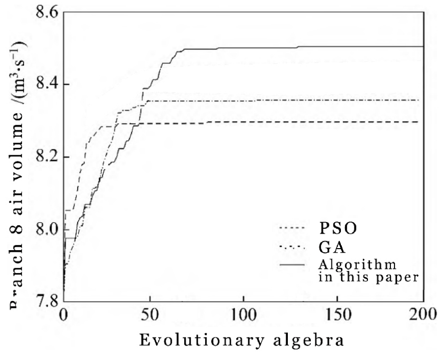

Fig. 3. Comparison of algorithm iterations

Through comparison, it can be seen that the algorithm described in this paper has the best optimization effect for the air volume regulation of the air path, up to A. In addition, among the three algorithms, the algorithm in this paper has the most iteration times and the operation time is not the fastest, but it is only 0.3 seconds longer than the PSO algorithm, and the overall performance is the best of the three algorithms. Therefore, use the same method to get the air volume of other branches, as shown in Table 4.

Table 4. Results of the whole ventilation network optimization

Parameter	Branch										
	1	2	3	4	5	6	7	8	9	10	11
Minimum air demand/ ($m^3 \cdot s^{-1}$)	42.68	18.32	9.23	8.98	12.07	22.54	18.97	5.46	6.03	13.87	20.05
Adjusted air volume/ ($m^3 \cdot s^{-1}$)	43.83	19.24	10.84	10.31	13.57	22.41	18.37	8.52	6.42	13.87	21.93
Parameter	Branch										
	12	13	14	15	16	17	18	19	20	21	
Minimum air demand/ ($m^3 \cdot s^{-1}$)	7.32	7.06	5.88	9.06	3.82	1.43	8.95	43.27	43.34	44.21	
Adjusted air volume/ ($m^3 \cdot s^{-1}$)	8.64	7.42	5.86	9.32	3.83	1.52	9.23	43.92	44.82	44.83	

Through the above process, the optimal scheme of fan ventilation regulation in B Mine of A Group in Tangshan was obtained, and the effectiveness and progressiveness of the algorithm proposed in this paper were verified.

6 Conclusion

This paper takes the mine B of Tangshan A Group as an example, establishes an optimization model based on the ventilation network, and uses the improved Grey Wolf algorithm to solve it. First, according to the constraints in actual production, establishes a mathematical model of air volume optimization close to the real environment, and then uses the improved Grey Wolf algorithm to find the optimal solution of the model, and describes the algorithm improvement process. Finally, the optimal air volume adjustment scheme for each branch of the ventilation network is given.

In the algorithm verification stage, due to the improvement of the Grey Wolf algorithm, the convergence speed of the algorithm did not reach the optimum. Therefore, the next research focus will be on how to improve the operation speed of the algorithm.

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