Energy Saving Schedule of Mine Drainage System Based on Particle Swarm Optimization

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Abstract. During mine construction and production, drainage system cost is the main component, so it is valuable to optimize its schedule to reduce the cost. Since many mines use time-of-use electricity, the paper proposes an algorithm to obtain the best schedule. The algorithm consists of two steps: predicting the water level using exponential moving average, and solving the optimal scheduling problem using particle swarm optimization. The particle swarm optimization is improved to make it fast convergent. Experiments are performed with the real data of a gold mine in China, and the result show that the proposed algorithm can reduce cost distinctly.

1. Introduction

During mine construction and production, the groundwater and surface water can leak into the mines, which is called mineral water. The accumulation of mineral water not only affects production, but also threatens the health and safety of underground workers. Therefore, it is necessary to drain away the water to ground in a timely manner, and the removal of groundwater and surface water from mines is referred to mine drainage. Drainage system cost is the main component of mine production cost, which accounts for about 17-40% of the total energy consumption of mines [1], so it is imperative to optimize the schedule of drainage system to save energy.

There are two main ways to reduce the operation cost of drainage system. The first one is to choose the appropriate devices and suitable running parameters according to the amount the mineral water. The second one is to schedule the intervals of drainage system to drain during non-peak period of time-of-use electricity fee. Since the drainage system cannot reform frequently, the second approach is more practical than the first one [2].

The energy saving schedule can be formulated as an optimization problem. In recent years, many swarm intelligence optimization algorithms are put forward according to the inspiration of nature population to feed, breeding, etc, such as particle swarm optimization (PSO), ant colony optimization (ACO), and moth-flame optimization (MFO). These algorithms are simple to implement and can arrive at the near-optimal solution of complex optimization problems faster than traditional optimization algorithms, so they are widely applied in many fields [3].

This paper aims to schedule the mine drainage system to save energy by water inflow prediction and PSO. The main contributions of the paper include:

1. It proposes a prediction method based on the exponential moving average to predict the water inflow amount.

2. It presents the energy saving schedule model of mine drainage system.
(3) It puts forward an improved PSO algorithm to solve the above problem. The organizations of the rest of the paper are as follows. Section 2 introduces the problem definition and related works. Section 3 presents the energy saving schedule of mine drainage system based on exponential moving average (EMA) and PSO. Section 4 proposes the experiments and analyzes the results. Section 5 concludes the paper.

2. Related Works
The simplified model of mine drainage system is shown in Fig. 1. The mineral water is drained from the points of water surge to a given water sump through pipelines, and then the water is drained to the ground through the drainage system consisting of several pumps. In order to reduce energy consumption, several water level sensors are installed in the water sump. When the water level is higher than a certain threshold, the water pump must be opened for drainage. When the water level is below a certain threshold, the water pump should be closed to stop drainage. In other cases, pumps can be turned on or off as needed. On the other hand, the peak-valley time-of-use price makes us try to drain water at non-peak period. Therefore, the drainage problem is to schedule the opening time of the drainage system to minimize the cost.

A hybrid Petri nets model for the optimal control of mine drainage systems is presented in [4]. This model combines continuous, controlled, and time delay Petri nets, where they are respectively used to describe and analyze continuous variables, allow feedback control, and assess the performance of mine drainage systems.

For the No. 14 Coal Seam of China’s Linnancang Coal Mine, a comprehensive model of the seepage field is undertaken in [5] to determine the appropriate water level in neighboring aquifers to reduce the likelihood of water inrush events, and it uses FEFLOW (Finite Element subsurface FLOW system) to optimize the mine drainage capacity.

![Fig. 1. The sketch of drainage system of mines](image)

There are two kinds of methods to optimize the energy of mine drainage system. The first kind is to choose the appropriate devices [1], such as the motor and pump unit. However, the replacement of equipment is not feasible in most cases, so we should schedule in the drainage system is to achieve the purpose of reducing energy consumption. An optimization model is given in [6,7] for the high energy consumption caused by uncertainty and irregularity running of mine drainage system. This model aims to minimize the energy consumption, and it is solved by hybrid genetic algorithm, but this method does not consider the change rule of water level. Some mine drainage systems use cascade pumping stations, so an optimization problem with objective function of minimal electricity fee based on time-of-use is proposed in [8,9], and it is solved by PSO or ACO [9]. The above methods don’t take the water inflow prediction into account, so a grey model of water inflow in tunnel and time with measuring data and
economic model are established in [10]. After predicting the water inflow, a coal mines pumping water pump is scheduled in non-peak periods.

Different from the above methods, this paper utilizes EMA to predict the water inflow, which is more precise than grey model used in [10], and it uses improved PSO to get the near-optimal solution of drainage system schedule.

3. Energy Saving Schedule using EMV and PSO

3.1 Problem Formulation

We formulate the problem as an optimization problem in first. Suppose one day is divided into \( n \) periods, and the electricity fee in \( i \)th period is \( c_i \). The drainage system needs to work at least once in one day. The power of drainage system is \( p \). So, the total cost of drainage system in one day is:

\[
P = \int_0^{24} p R(t) C(t) \, dt
\]

(1)

where \( C(t) \) is the function of electricity fee, and \( R(t) = 0 \) if the drainage system is off at time \( t \), \( R(t) = 1 \) if the drainage system is on at time \( t \). Since time-of-use price is used, Equ. (1) can also be:

\[
P = \sum_{i=1}^{n} p c_i l_i
\]

(2)

where \( l_i \geq 0 \) is the length of running time of drainage system in \( i \)th period.

When the water level is higher than a given threshold, the drainage system must be started. Suppose the water level is real-time monitored, we can predict the water level using moving average method, and then schedule the drainage system based on the prediction and time-of-use price.

3.2 Water Level Prediction using Exponential Moving Average

We use the second-order EMA to predict the water level. This method is based on basic and second-order exponential smoothing. Let \( w_t \) be the real water level at time \( t \), and \( w_t^{(1)} \) be the basic exponential smoothing value of water level at time \( t \). The basic exponential smoothing formula is:

\[
w_t^{(1)} = \alpha w_t + (1 - \alpha) w_{t-1}^{(1)}
\]

(3)

where \( \alpha \) is smoothing factor. Let \( w_t^{(2)} \) be the second-order exponential smoothing value of water level at time \( t \). The second-order exponential smoothing formula is:

\[
w_t^{(2)} = \alpha w_t^{(1)} + (1 - \alpha) w_{t-1}^{(2)}
\]

(4)

Let \( \tilde{w}_{t+T} \) be the prediction value of water level at time \( t + T \), we have

\[
\tilde{w}_{t+T} = a_t + b_T
\]

(5)

where

\[
\begin{aligned}
a_t &= 2w_t^{(1)} - w_t^{(2)} \\
b_t &= \frac{\alpha}{1 - \alpha}(w_t^{(1)} - w_t^{(2)})
\end{aligned}
\]

(6)

3.3 Mine Drainage System Scheduling

Based on the above subsections, we can present the scheduling algorithm using PSO. PSO is a population based stochastic optimization technique inspired by social behavior of bird flocking or fish schooling. In the mine drainage system scheduling problem, the objective function is Equ. (2), where \( (l_1, l_2, \ldots, l_n) \) is the variable vector to be solved to minimize \( P \). Suppose PSO consists of \( M \) particles which represent a candidate solution to the objective function. Particle \( i \) occupies three \( n \)-dimensional vectors \( D_i, E_i, V_i \) representing its current coordinate, previous best coordinate, and current velocity.
Besides, $G$ denotes the position of the best particle so far. PSO tries to arrive at the global optimal value of the given objective function iteratively. In each iteration, each particle updates its velocity and position, after evaluating its fitness, on the basis of the following formula:

$$
\begin{align*}
V_{ij} &= \omega V_{ij} + c_1 \varphi_{ij}(E_{ij} - D_{ij}) + c_2 \varphi_{2j}(G_{j} - D_{ij}) \\
D_{ij} &= D_{ij} + V_{ij}
\end{align*}
$$

(7)

where $c_1$ and $c_2$ are cognitive and social coefficients, respectively, $\varphi_{ij}$ and $\varphi_{2j}$ are random numbers uniformly distributed in $(0,1)$, and $\omega$ is the inertia weight which is linearly decreased as

$$
\omega = \omega_{\text{max}} - \frac{\omega_{\text{max}} - \omega_{\text{min}}}{k_{\text{max}}} \times k
$$

(8)

where $k_{\text{max}}$ is the maximum number of allowable iterations, $\omega_{\text{max}}$ and $\omega_{\text{min}}$ are maximum and minimum weights, respectively, and $k$ is the current iteration.

In order to make PSO converge rapidly, we present the following improvements of PSO. During each iteration, the particles are sorted according to their fitness (i.e., the value of objective function at particles’ positions) in ascending order. Let $F_i$ be the fitness of particle $i$, the sorting result satisfies $F_i \leq F_{i+1}$, $i = 1, 2, \ldots, M - 1$. After sorting, the last half particles update their positions as

$$
D_{i,j} = D_{i,j} + \rho_{ij}, i = 1, 2, \ldots, \left\lfloor \frac{M}{2} \right\rfloor; j = 1, 2, \ldots, n
$$

(9)

where $\rho_{ij}$ is a random number uniformly distributed in $[-0.5, 0.5]$. This equation replaces the positions of the last half particles with positions close to the first half ones.

The basic idea of optimal drainage system scheduling includes two stages. In the first stage, EMV is used to predict the water level. In the second stage, PSO is used to optimize Equ.(2) with the water level predictions. The following algorithm gives the details.

**Algorithm 1: Drainage System Scheduling Algorithm**

1. Get the history water levels;
2. Predict the water level in next $k$ times using Equ.(3)-(6);
3. Generate $M$ particles randomly in the search space;
4. $k \leftarrow 1$;
5. While $k \leq k_{\text{max}}$ do
6. Compute the fitness of all particles;
7. Compute $E_i$ and $G$;
8. Sort and update particles’ positions using Equ. (9);
9. Update particles using Equ. (7);
10. Update $\omega$ using Equ.(8);
11. End while

In this algorithm, line 1 gets the history water level data. Generally, the sensors in water sump reports water level at a given interval, such as half an hour, so the history data is the real water level in the past hours or days. In the next step, EMA is used to predict the water levels in the next several hours. Lines 4-11 are the PSO-based method to solve Equ. (2). The constraint is the water level must be less than the given threshold $\Omega$, which means the drainage system must be powered on once $w_t \geq \Omega$. In order to minimize the energy, the drainage system can also be powered on when $w_t < \Omega$.

4. **Experiments and Analysis**

We use the real data in JinChiLing Gold Mine in Zhaoyuan, China to verify the performance of the proposed algorithm. The water level data is one water sump in this mine, from January 1, 2018 to May 31, 2018. The given water level threshold $\Omega = 10$ m. The water levels are measured every half an hour, and Table 1 presents a little part of these data while the drainage system is off.
Table 1 Water level examples

| time | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|------|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|
| level (m) | 2.1 | 3.0 | 2.6 | 2.8 | 3.4 | 3.4 | 3.5 | 3.7 | 3.8 | 4.1 | 4.6 | 4.8 | 5.1 | 5.2 | 5.4 |

The electricity fee is divided into three periods. 8:00 to 11:00 and 18:00 to 21:00 are two peak periods, and the electricity fee is RMB 1.252 YUAN per KWh (kilowatt-hour). 6:00 to 8:00 and 11:00 to 18:00 are two flat periods, and the electricity fee is RMB 0.782 YUAN per KWh. The others are valley periods, and the electricity fee is RMB 0.370 YUAN per KWh.

The parameters of EMV and PSO are: $\alpha = 0.7$ to make the real data more important than the predicting data; $M = 50$, $\omega_{\text{max}} = 0.9$, $\omega_{\text{min}} = 0.1$, $k_{\text{max}} = 300$, $c_1 = c_2 = 1.7$.

We first check the accuracy of EMV to predict the water level. Using the water levels shown in Table 1, we predict the water level using EMV with $T = 1, 2, 3$ in Eq. (5). The results are shown in Fig. 2, which shows that the prediction accuracy of EMV is very high.

Fig. 2. Water level prediction using EMV

Fig. 3 shows the total electricity fee comparison between the real and optimized ones per month. The results show that the proposed method can decrease the total electricity fee. In detail, the optimized fee is respectively 1.14%-9.87% and 21.76%-50.12% of real fee during peak period and flat period, while the optimized fee is 160-180% of real fee during valley period. This indicates that the running time of the drainage system is greatly reduced in the peak period and greatly increased in the valley period. The total electricity fee can be reduced to 64.15%-87.92% of the real fee.

5. Conclusion

Drainage system cost is the main component of mine production cost, so it is imperative to optimize the schedule of drainage system to save energy. This paper presents an EMV and PSO based optimization algorithm to schedule the drainage system, where EMV is used to predict the water level on the basis of the history data, and PSO is used to solve the optimized problem to obtain the best schedule. We use the data from a gold mine in Zhaoyuan, China to verify the method, and the results show that the proposed method can reduce the electricity fee. However, this method is applied to the drainage system with only one pump. In future, we will focus on the system with a group of pumps of different power.
Fig. 3. Comparison between real and optimized electricity fees

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