Power system parameter matching and particle swarm optimization of battery underground loader

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Abstract
As part of the ongoing research into new energy technology, battery-powered underground loaders have emerged. However, there have been few studies on power system optimization and matching for these battery underground loaders to date. This paper, which takes a 3-m³ battery underground loader as its research object, determines the loader’s optimal operating point through study of the power response characteristics of the loader’s motor under various working conditions. The effects of different power batteries on the working conditions are analyzed, and the loader’s component parameters are matched. Additionally, an optimization model of the driving system of the battery underground loader is constructed. On the basis of the driving operation characteristics of the loader, the particle swarm optimization algorithm is proposed to optimize the operating conditions of the loader’s driving motor. The results show that the transmission ratio is reduced after optimization. The single-cycle energy consumption is reduced by approximately 1.98% and the number of cycles in the health status of the power battery’s state-of-charge increases by approximately 1.91%, which verifies the feasibility of use of the particle swarm algorithm in the loader optimization problem. This work can serve as a reference for related theoretical research on underground loaders.

Keywords
Battery underground loader, parameter matching, driving motor operating condition, particle swarm optimization, state-of-charge, energy consumption

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Introduction
Underground loaders are widely used in mine engineering. However, these underground loaders consume a great deal of energy and cause serious environmental pollution at the same time. With both their energy sources and environmental problems becoming increasingly prominent, it is now imperative to reduce the energy consumption of and emissions from these loaders. Therefore, battery-powered underground loaders represent an important development direction to reduce the energy consumption and the emissions of these loaders.1

Research about battery underground loaders has been published recently. Varaschin and De Souza performed an evaluation study of the economic benefits of replacing...
supporting diesel loaders with electric loaders and established engineering models for comparison; their results showed that use of electric loaders can greatly reduce emissions, along with ventilation, maintenance and other costs. Jacobs conducted a cost/benefit analysis of the implementation of electric load-haul-dump (LHD) vehicles in Western Australian underground hard rock mines and concluded that use of battery loaders is one possible solution to the problems with loader towing cables in these mines. Lehmuspelto et al. described the requirements that must be taken into account during the design and dimensioning of an electromechanical driveline for an underground mining loader and proposed a modular driveline concept. Hentunen et al., who developed and verified the battery pack for the above loader, stated that the duty cycle could be used as a validation power profile. De Almeida evaluated the thermal impact of an underground mining vehicle’s battery pack and reported on the thermal impact of the surrounding environment on the mining vehicle. The energy consumption of battery electric vehicles during driving and other processes was analyzed by Kukkonen and the corresponding energy consumption information was obtained for different vehicles.

At the same time, the particle swarm optimization (PSO) algorithm has been studied by numerous researchers. Ryalat et al. proposed use of the PSO algorithm to optimize an interconnection and damping assignment passivity-based control (IDA-PBC) device and the effectiveness of this controller was verified using the PSO tuning method. Sun et al. applied the PSO algorithm to correlation electromagnetic analysis (CEMA) to solve optimization problems with high dimensions and complex structures and an improvement of approximately 13.72% was reported for the corresponding case. Ye and Li proposed a PSO-proportional–integral–derivative (PID) control strategy to eliminate power deviations rapidly, and approximate global optimization of the electric vehicle energy management strategy was achieved. Yin et al. studied use of the PSO algorithm to optimize the energy management of power split hybrid electric vehicles and showed that the final value of the battery’s state-of-charge can be maintained within a reasonable range. Shen and Chen used the PSO algorithm to optimize multi-depot location decisions and reduced their average routing distance by approximately 13.16%. Chiu et al. investigated a PSO-reinforced fuzzy PID controller for quadrotor attitude control and found that the new elite control parameter gains could be generated and updated rapidly. Chen and Shen used the PSO algorithm to optimize dynamic search control for project scheduling problems and solved an activate operating priority problem and an activate operating mode sub-problem.

When compared with conventional cars, underground loaders operate under very different conditions. Although there have been some previous studies of battery underground loaders, there has been little research on power system parameter matching for battery underground loaders. Some research on PSO is also available, but few studies have been reported about the use of PSO on battery underground loaders. First, this article takes a 3-m³ battery-type underground loader as its research object; the regular characteristics of the loader’s battery and motor are studied under various working conditions and the power system parameters are matched. Second, to improve the energy utilization rate of the entire machine, PSO is used to optimize the gearbox transmission ratio to minimize the vehicle’s energy consumption during a single working condition cycle. Finally, the optimized transmission ratio and the energy consumption are both reduced after the optimization process, the feasibility of use of the PSO algorithm is verified, and the optimized results can provide a reference point for related theoretical research.

### Working conditions of underground loader

The working environment for underground loaders is poorly ventilated and humid, and the roadways are relatively narrow, as shown in Fig. 1.

The loader’s working operating conditions are mainly composed of basic operational segments, including driving to the stockpile, insertion into the stockpile, retreating with a full load, driving to the transporter, and returning with zero load. Because of the organization of the loader and the periodicity of its operation, an “L” type working path is typically adopted as a basic working path for the loader. The working cycle and the process diagram are shown in Fig. 2.

Section I, which is a revolving path with a length of 50 m, is used as a buffer stage, and the transportation distance in Section II is 100 m. At present, there is no cyclic working condition standard for use with underground loader operation terminals. In this paper, probability similarity theory and an evaluation method for the loader working conditions are used, and the cyclic working condition is created for the 3-m³ underground loader; the cycle working condition diagram created in this process is as shown in Fig. 3.

![Figure 1. Working environment of the underground loader.](image-url)
To match these driving conditions with the actual L-shaped operating conditions, the original operating conditions must be modified. However, in view of the parking and unloading times required, the cycle period length is modified to 50 s. Integral calculations are performed on each stage of the hypothetical cycle working conditions and the displacement is obtained for each stage; these results are then compared with those obtained under the actual L-shaped working conditions, as shown in Table 1.

The results in Table 1 show that the simulated operating conditions are basically consistent with the actual operating conditions.

Motor parameter matching

Analyses of loader operations are mainly divided into two types. The first is the force analysis during shoveling operations and the second is the force analysis during transportation operations. These transportation operations are subdivided into flat road transportation and slope transportation. The flat road transportation is classified as slope transportation during this study, where the slope is zero. Under these two working conditions, the torque of the electric motor is converted into traction through the loader's transmission system to drive the vehicle. The traction works to overcome the resistance of the loader during driving. Therefore, on the basis of the vehicle dynamics, the force balance formula under the two working conditions above can be expressed as follows:

\[ F_z = F_f + F_w + F_i + F_j + F_c, \]

where \( F_z \) is the rolling resistance and \( F_f = mgf \); \( F_w \) is the air resistance, where \( F_w = \frac{2c_D A u^2}{21.15} \); \( F_i \) is the slope resistance, where \( F_i = mg \sin \alpha \); \( F_j \) is the acceleration resistance, where \( F_j = \delta \Delta u \); \( F_c \) is the insertion resistance; \( m \) is the total weight; \( f \) is the rolling resistance coefficient; \( \delta \) is the mass conversion factor; \( \alpha \) is the acceleration; \( \alpha \) is the climbing angle; \( C_D \) is the drag coefficient; and \( A \) is the frontal area.

According to the dynamic principle and the loader's working condition characteristics, the expressions for each component force can be obtained as follows:

\[
\begin{align*}
F_i &= \frac{Ti\eta}{r_k} \\
F_f &= mgf \\
F_w &= A_c F_A u^2 \\
F_i &= mg \sin \alpha \\
F_j &= \frac{5\delta m \Delta u}{18}  \\
F_c &= F_i + F_j + F_c
\end{align*}
\]

where \( T \) is the motor torque; \( i \) is the total transmission ratio; \( r_k \) is the rolling radius of the underground loader tires; \( \eta \) is the total efficiency of the transmission system; \( A_c \) is the coefficient of air resistance; \( m \) is the total weight; \( F_A \) is the frontal area; \( u \) is the machine speed; \( \delta \)
is the rotation mass conversion factor; and $\alpha$ is the climbing angle.

The relationship between the driving force and the motor power is given as follows:

$$F_t = \begin{cases} 3600 \frac{p_{\text{max}} \eta_T}{u_e}, & u \leq u_e \\ 3600 \frac{p_{\text{max}} \eta_T}{u}, & u > u_e \end{cases},$$

where $p_{\text{max}}$ is the motor’s peak power; $\eta_T$ is the overall efficiency; $u$ is the current driving speed of the loader; and $u_e$ corresponds to the loader driving speed at the rated motor speed.

**Selection of motor rated power**

The rated power mainly affects the energy conversion efficiency of the entire machine. Based on the fitting cycle conditions, a probabilistic method is used to match the rated power of the motor accurately.\(^{18}\) Because of the overload capacity of the motor, the motor’s efficiency is higher in the range from 0.8 to 1.1 times the rated power than in other areas of this range. Therefore, when determining the motor’s rated power, the fact that the working point of the loader is distributed within this concentrated area near the rated power should be considered.

According to the law of conservation of energy, the power of the loader during driving is given by:

$$P = \frac{F_z u}{3600 \eta_T}$$

During the operating cycle of the underground loader, the amount of labor consumed in the transportation process accounts for 60% to 70% of the cycle time, and most of the working conditions are the flat road transportation type.\(^{19}\) Therefore, when the rated power is calculated, the slope resistance can be ignored. Using the cycle conditions created above, the driving load power curve of the loader can then be obtained, as shown in Fig. 4.

Figure 4 shows that the wave crests basically appear during rapid acceleration and during the shovel loading conditions. Among these crests, when the power is positive, the motor is in the electric running state, but when the power is negative, the motor is in the braking running state. Because the loader’s braking process still uses the original braking method, neither the motor braking nor the recycling of the braking energy are considered in the work in this article. To obtain the distribution of the power points, the driving load power is sampled when the motor is in the electric running state using a sampling time of 0.01 s. Using a probability statistics method, a histogram of the driving power spectrum distribution of the loader is obtained, as illustrated in Fig. 5.

Through analysis and study of the time-domain and frequency-domain characteristics of the load power of the loader under the cycling conditions, it is found that the driving load power of the loader is mainly distributed within the 0–44 kW range. The whole range can be divided into 11 cells in the unit of 4 kW, and each cell has its corresponding frequency of occurrence of working points. 15.8% refers to the frequency of occurrence of working points of the loader distributed in the range of 20–24 kW accounting for 15.8% of the total frequency of occurrence of working points of all cells. When this figure is combined with the motor efficiency characteristics, 22 kW is used as the rated power of the motor in this study. 90 kW is regarded as the rated power of the loader and this power is greatly reduced when compared with that of the original car motor used in the loader.

| Driving operation fragment       | Toward the material pile (m) | Full load back (m) | Heading toward the transporter (m) | Back without load (m) |
|----------------------------------|-----------------------------|-------------------|----------------------------------|----------------------|
| Actual L-shaped working conditions | 50                          | 100               | 50                               | 100                  |
| Created cycle working conditions | 49.96                       | 98.75             | 49.52                            | 99.63                |

**Figure 4.** Driving load power of the underground loader.
Selection of motor peak power

The motor’s peak power characteristics determine the overall working performance of the underground loader under the plug-in working conditions, the climbing working conditions and the acceleration working conditions. Both the power and the efficiency of the underground loader have been considered here. When the results are combined to give the peak power operating characteristic curve of the motor, as shown in Fig. 6, point A represents the optimal operating point of the underground loader under short-term conditions. Therefore, the peak operating characteristics of the motor are analyzed in this article from three perspectives: climbing ability, acceleration ability, and ability for insertion into a material pile.

Maximum climbing condition analysis.

The operating slope for most underground loaders is in the range between 10% and 20%. This paper uses the maximum gradeability of 20% as the standard for the research.

Under the climbing conditions, when the loader moves forward at a stable speed, the loader then mainly overcomes the climbing resistance, the rolling resistance and the air resistance to perform its work. Therefore:

\[
\begin{align*}
\text{\textbf{P}}_{\text{max}} &= \frac{F_{\text{ul}}}{3600n_T} \\
\text{\textbf{F}}_{\text{t}} &= F_{\text{f}} + F_{\text{i}} + F_{\text{w}}
\end{align*}
\]  

(5)

Using Eqs. (1) and (2), the maximum climbing slope of the loader can be expressed as follows:

\[\alpha = \arcsin \left( \frac{F_{\text{f}} - F_{\text{i}} - F_{\text{w}}}{mg} \right), \]

(6)

where \(\alpha\) is the climbing angle; a steeper slope corresponds to a better climbing ability for the loader, and vice versa.

The loader’s climbing ability is usually expressed using the climbing angle, and the climbing angle is usually expressed based on the inclination, which is given by the following expression:

\[\text{Slope} = 100 \tan \alpha\]

(7)

Through analysis of the relationship between the peak power of the motor and the climbing angle of the loader, the curve shown in Fig. 7 can be obtained, where the climbing speed is assumed to be 2.7 km/h.

Figure 7 shows that as the peak power of the motor increases, the maximum gradeability that the loader can
overcome also increases and this relationship remains basically linear; this is similar to the impact on the maximum speed. However, the difference between the no-load state and the full-load state becomes increasingly large with increasing peak power.

Loader acceleration performance analysis. Because of the need for the operation to be performed and the space requirements in the mine, loaders are frequently accelerated. The standing start acceleration time of the loader is used as one indicator to evaluate the loader’s dynamic performance. To reflect the acceleration process of the loader and its work efficiency, the time required to accelerate to one-third of maximum speed is used as a parameter to test the acceleration performance of the loader, where this time is given as follows:

$$ t = \frac{1}{3.6} \int_{0}^{\delta_{u \text{act}}} \frac{\delta m}{F_1 - (F_1 + F_w)} \, du $$

(8)

Among these parameters, the driving force $F_1$ is given in Eq. (3).

Through analysis of the effect of the motor’s peak power on the acceleration time of the loader, the diagram shown in Fig. 8 is obtained. The acceleration time means the time required for the loader to accelerate to 10 km/h in first gear in the full power state.

As shown in Fig. 8, when the peak power of the motor increases, the time required for the loader to accelerate to a specific speed becomes increasingly short. Furthermore, the difference between the two acceleration times under the no-load and heavy-load conditions also becomes increasingly small. When the motor’s peak power value is low, it has a significant effect on loader acceleration. With increasing peak power, however, the curve gradually becomes flat. This change indicates that the impact of the peak power is becoming smaller. Therefore, when the acceleration time of the loader is used as the power performance index, the significance of the impact of the peak power on the loader’s acceleration performance decreases when the power increases.

Analysis of insertion conditions. The depth of a single insertion into a material is usually used to reflect the performance of the loader. Under the plug-in working conditions, where the loader operates at a stable speed, the relevant formula is:

$$ \begin{cases} P_{\text{max}} = \frac{F_{\text{mu}} \eta_\text{t}}{3600} \\ F_1 = F_t + F_i + F_w + F_c \end{cases} $$

(9)

In this paper, Coulomb’s earth pressure theory is applied to analyze the insertion resistance of the loader. It is assumed that the shovel loading method is based on a flat shovel and that the reclaiming stroke is consistent with the insertion depth. The relevant formula in this case is:

$$ F_C = F_1 + F_2 + F_3 + F_4 + F_5, $$

(10)

where $F_1$ is the force of the material on the bottom edge, and $F_1 = (C_0 + K \gamma \tan \alpha) bt_1$; $F_2$ is the friction force between the bottom surface of the bucket floor and the material, where $F_2 = (C_0 + K \gamma bL \tan \alpha/2) \mu bL$; $F_3$ is the force of the material acting on the left and right side edges, where $F_3 = (2C_0 + K \gamma bL \tan \alpha/2 - \tan \beta) \tan \alpha$; $F_4$ is the friction force acting between the material and the outer surfaces of the left and right side plates of the bucket, where $F_4 = \mu \gamma b^2 L^2 \tan \alpha \tan \beta$; and $F_5$ is the horizontal component of the force exerted by the material inside the bucket, where $F_5 = \frac{1}{2} \gamma aL^2 b \tan^2 \alpha$. $C_0$ is a parameter that characterizes the shear performance of the materials; $\gamma$ is the weight of the material; $K$ is the Rankine passive earth pressure coefficient, where $K = \tan^2(45^\circ + \frac{\varphi}{2})$; $\varphi$ is the internal friction angle of the material; $\alpha$ is the accumulation angle of the material; $\beta$ is the opening angle of the bucket; $b$ is the bucket width; $t_1$ is the thickness of the bottom edge of the bucket; $t_2$ is the thickness of the left and right side edges of the bucket; $\mu$ is the friction coefficient between the bucket body and the material; and $L$ is the insertion depth for a single bucket, which has a value of 0.7 m.24

It is assumed that the loader insertion speed is 1 km/h during insertion. According to the analysis above, the relationship between the peak power of the motor and the insertion force of the loader acting on the flat shovel can be obtained as shown in Fig. 9.

Figure 9 shows that a linear relationship between the peak power of the motor and the insertion force is
obtained, where higher power indicates a greater insertion force. In the actual work, the relationship between the insertion force and the driving force of the entire machine is often linear.

**Comprehensive analysis of motor peak power.** Through a comprehensive analysis of the influential factors under the three working conditions, the correlation between the motor’s peak power and its rated speed jointly determines the dynamic characteristics of the loader. For convenience of analysis here, the relationship above is expressed in the form of a graph, as shown in Fig. 10.

In Fig. 10, curve A represents Eq. (8), curve B represents Eq. (10), curve C represents Eq. (11), and curve A and curve B divide the area on the right side of curve C into three parts, comprising zone I, zone II and zone III. The area enclosed by curve A, curve C and the abscissa axis is zone IV. Among these zones, the peak power and the rated speed of zone I can meet the requirements of three short-term operating conditions. However, zone II cannot meet the requirement for maximum gradeability, zone III cannot meet the requirements for maximum gradeability and plug-in working conditions, and zone IV can meet the requirements for maximum gradeability and plug-in working conditions but cannot meet the acceleration time requirement. All points on the left half of curve C are unable to meet the acceleration time requirements.

In summary, the optimal operating point is located at the intersection of curve A and curve C. The peak power and the rated speed corresponding to this point meet the power requirements for the three short-term working conditions and can ensure a specified working efficiency for the loader at the same time.

Based on the relationship between the motor speed and the vehicle speed, the rated speed and the peak speed of the motor can be obtained as follows:

\[
\begin{align*}
   n_e &= \frac{u_e i_q i_{TB}}{0.337 r_d} \\
   n_{\text{max}} &= \frac{u_{\text{max}} i_q i_{TB}}{0.337 r_d}
\end{align*}
\]

Among these parameters, \( u_e \) is the vehicle speed when the motor is running at the rated speed in first gear; \( u_{\text{max}} \) is the maximum driving speed of the loader; \( r_d \) is the tire radius of the loader; \( i_q \) is the wheel drive ratio; \( i_g (g = 1, 2, 3) \) is the gearbox drive ratio; and \( i_{TB} \) is the torque converter transmission ratio. During high-load operation, the loader uses first gear to provide a greater driving force. When driving at its highest speed, the gearbox is in third gear.

Based on the analysis provided above, the performance parameters for the motor drive system that can match the loader are shown in Table 2 below.

### Battery parameter matching

At present, the most commonly used power batteries include lead-acid batteries, nickel-metal hydride...
Ni-MH) batteries and lithium iron phosphate (LiFePO4) batteries. It is assumed that the voltage platform is 380 V, the peak power of the motor is 50 kW, and the rated speed is 1000 r/min. The effects of the three commonly used battery types listed above on the maximum speed, the climbing ability and the acceleration performance of the underground loader are analyzed using these parameters.

Figure 11 shows that the effects of the different types of battery packs on the maximum loader speed are all basically the same, but the curve representing the lead-acid battery has the highest slope; this indicates that with increasing battery capacity, the maximum speed index of the lead-acid battery loaders will show the greatest decline, followed by that of the Ni-MH battery, and the LiFePO4 battery shows a slower decline and a slope that tends to be almost flat.

Figure 12 shows that the effects of the three types of battery pack on the loader’s gradeability are basically the same; when the battery capacity increases, the gradeability decreases in tandem, but the maximum gradeability of the LiFePO4 battery is the highest of the three types. The degree of the slope decreases more slowly as the battery capacity increases.

Figure 13 shows that as the battery capacity increases, the acceleration time of the LiFePO4 loader shows only a very small difference. Within the 200 Ah to 800 Ah range, the acceleration time difference is only 0.3 s. However, the Ni-MH and lead-acid battery capacities have greater effects on the loader acceleration time.

To enable further study of the influence of power battery parameters on the battery life of underground loaders, the loader driving distance on flat roads at a constant speed is selected as the index for consideration of the endurance of the loader, and its driving range is given by:

\[
S = \frac{E}{F_1},
\]

where \(E\) is the energy output of the motor.

An analysis is performed when the operating condition of the selected loader is the full load condition and the operating speed is 2.7 km/h, and the resulting relationship between the battery capacity and the loader driving range is as shown in Fig. 14.

As shown in Fig. 14, when the battery capacity is small, the loader mileage is almost the same for the three battery types. However, when the battery capacity gradually increases, the gaps between the performances of the three batteries also become increasingly large. The curve for the LiFePO4 battery is almost a linear straight line, demonstrating its performance advantage in terms of the driven distance. When the capacity of
When the lead-acid battery increases, the curve then increases more gently, indicating that its energy utilization efficiency is reduced, and the conversion efficiency of the entire machine is not good. All three battery curves tend to slow down, and the reason for this change can be explained as follows. Increasing battery capacity means that the mass of the entire machine is also increased. It can therefore be seen that the capacity and the mass of the battery are contradictory variables. An increase in capacity will also inevitably lead to an increase in the mass of the entire machine and a reduction in its economy. To study the relationship between the capacity and the mass of the battery pack, the parameter $K_{SM}$ is used. This relationship can be expressed as follows:

$$K_{SM} = S_{soc}/M_{bat},$$

where $K_{SM}$ is the mass ratio coefficient; $M_{bat}$ is the total mass of the battery pack; and $S_{soc}$ is the state-of-charge of the battery, $K_{SM}$ can reflect the energy utilization efficiency of the underground loader and also determines the driven distance.

Figure 15 shows the relationship between the battery capacity and $S_{soc}$. The value of $S_{soc}$ is the performance at the time when the loader is fully loaded and is driving for 10 km at a speed of 2.7 km/h.

As shown in Fig. 15, when the battery capacity increases, the $S_{soc}$ value of the battery pack also becomes increasingly large, which is consistent with the law of the relationship between the battery capacity and the driving range. It can thus be concluded that when the battery capacity increases, the remaining power in the battery pack, which can be used for continuous loader operation, also increases. In addition to studying the relationship between the battery capacity and $S_{soc}$, it is also necessary to study the relationship between $K_{SM}$ and the battery pack capacity because $K_{SM}$ represents the amount of electricity consumed per unit of battery pack mass. A larger value of this coefficient denotes lower energy consumption because of the attached weight of the battery pack and is more beneficial to the operating efficiency of the machine overall. Therefore, the three battery packs above are also used as objects to study the effects of different battery pack capacities on $K_{SM}$. Based on this research and subsequent analysis, Fig. 16 is obtained.

As shown in Fig. 16, the $K_{SM}$ value of the LiFePO$_4$ battery is much higher than that of the other two batteries, which illustrates that the effect of the reduction in overall battery efficiency caused by the increase in the battery mass is relatively small; this also verifies the theory that the LiFePO$_4$ battery is better than the other two batteries when applied to loaders. When the battery capacity increases continuously, $K_{SM}$ decreases gradually, which means that the efficiency of the entire machine is reduced. In other words, the increase in the

![Figure 14. Relationship between battery capacity and driving range.](image)

![Figure 15. Relationship between battery capacity and state-of-charge.](image)

![Figure 16. Diagram of relationship between battery capacity and $K_{SM}$.](image)
total battery capacity has a specific negative impact on the energy conversion efficiency of the entire machine.

The analysis above indicates that a bigger battery pack capacity is not necessarily better for the machine overall. As the battery pack capacity increases, the power performance (with the exception of the driven distance) and the economic performance will both decrease. Therefore, based on the need to meet the basic operating time requirements of the loader, a smaller battery capacity will lead to a better comprehensive performance for the machine overall.

Based on the analysis above, the performance of the LiFePO4 battery combination on the loader is better than that of the other two battery types. The important reason for this performance difference is that the electrodes of lithium-ion batteries are made from lightweight lithium. Carbon and lithium are highly reactive elements. In addition, lithium-ion batteries do not need to be discharged completely and they do not have any memory effect, while some other batteries do have such effects.26

The advantages of LiFePO4 batteries were thus confirmed by the analysis above, and this battery type is selected as the power source for subsequent analysis and research. However, in a loader, more attention is paid to the operating time and the cycle times of its state-of-charge (SOC) in a healthy state. Given that the energy consumption of the loader basically changes periodically, the number of cycles can be used to provide a comprehensive reflection of the cruising range and running duration of the loader, and the number of cycles is used as a parameter to determine the total battery power.

By integrating the power spectrum shown in Fig. 4, the motor’s energy output during a single loader cycle can be described as follows:

$$E = \int_0^T Pdt, \quad (14)$$

where $T$ is the time taken for a single cycle.

From the working characteristics of the loader, the operating time of the entire machine is 8 h, the number of loader operating cycles is 576, and the total power of the power battery is given by:

$$E_B = \frac{nE}{q\eta_q\eta_c\eta_{ih}\eta_m}, \quad (15)$$

where $q$ is the depth of the discharge; $\eta_q$ is the average discharge efficiency of the power battery; $\eta_c$ is the motor controller efficiency; $\eta_{ih}$ is the inverter efficiency; $\eta_m$ is the average motor efficiency; and $E_B$ is the total power of the power battery, which can also be expressed as:

$$E_B = U_b C_b n_b, \quad (16)$$

where $U_b$ is the operating voltage of LiFePO4; $C_b$ is the single battery capacity; and $n_b$ is the number of battery cells.

Based on the analysis above, the performance parameters of the loader power battery can be matched as shown in Table 3.

### Power system parameter optimization

#### Establishment of power system model

Next, a mathematical model of the battery-type underground loader power system is established based on the analysis above, where this system includes wheel modules, gearbox modules, motor modules and battery modules.

**Wheel modules.** The wheel output speed is calculated using the driving speed $u$ of the loader:

$$n_W = \frac{u}{2\pi r S}, \quad (17)$$

where $s$ is the wheel slip rate:

$$S = 0.1 \frac{F_t}{G_o} + \delta_1 \left(\frac{F_t}{G_o}\right)^8, \quad (18)$$

where $\delta_1$ is an empirical coefficient and has a value in the 5.48–9.25 range; and $G_o$ is the attached gravity.

**Gearbox modules.** The joint action of the gearbox drive axle and the hydraulic torque converter is used to change the direction and magnitude of the torque transmission to adapt to the different needs of the loader under operational and driving conditions. For convenience of calculation here, it is assumed that the torque converter transmits the torque with a constant torque coefficient. By combining the three elements above into a single module, the input speed and torque are given by:

$$\begin{cases} n_T = n_W i_q i_{TB} \\ T_T = \frac{F_t}{i_q i_{TB} \eta_T} \end{cases}, (19)$$

To avoid the interference from the shifting rules during optimization of the transmission ratio and to ensure the continuity of the loader’s driving force, the gearbox

| Table 3. Power battery performance parameters. |
|---|---|---|---|---|
| Parameter | Type | $U_b$ (V) | $C_b$ (A·h) | $E_b$ (kW·h) | $n_b$ |
| Numerical value | LiFePO4 | 3.2 | 5.2 | 136.8 | 7113 |
uses a shift point following strategy, which means that the motor rated speed corresponding to the speed of each gear reduction ratio is taken as the shift point.

**Motor modules.** Depending on the working condition of the motor, the efficiency of the motor is dependent on its real-time speed and torque. Therefore, the efficiency characteristic of the motor is a function of both its speed and its torque:

\[
\eta_m(t) = F(T_m(t), n_m(t))
\]  
(20)

The relationship between the motor speed and the driving speed of the loader is:

\[
n = \frac{n_i}{0.377 n_f}
\]  
(21)

The characteristic curve expression of the motor output power is:

\[
T_{\text{max}} = \begin{cases} 
T_{\text{peak}}, & 0 \leq n \leq n_e \\
\frac{9550 p_{\text{peak}}}{n}, & n_e \leq n \leq n_{\text{max}}
\end{cases}
\]  
(22)

Based on the law of similarity of motors, a three-dimensional diagram of the motor efficiency obtained using the multivariate linear fitting method is shown in Fig. 17.

**Battery modules.** The electrical energy from the power battery is transmitted to the motor through an inverter and the motor controller. Therefore, the power consumed at the battery output is:

\[
p_{\text{bat}}(t) = \frac{T_m(t)n_m(t)}{9550p_{\text{peak}} n_e \eta_i \eta_d}
\]  
(23)

**Particle swarm optimization**

The particle swarm algorithm is an optimization algorithm that simulates the migration process of birds when foraging. When compared with genetic algorithms and the simulated annealing algorithm, the particle swarm algorithm has advantages that include simplicity, fast convergence speeds and fewer parameter setting requirements, which means that this algorithm is highly suitable for solution of the transmission ratio parameter optimization problem described in this article. In the particle swarm algorithm, each optimization problem solution is imagined as a bird, called a “particle”, and all particles are searched within a D-dimensional space (Fig. 18).  

The random particles (random solution) find the optimal solution to the problems through an iterative approach. The positions and velocities of the particles must be updated for each iteration. The velocity update formula is:

\[
v^{k}_{id} = w v^{k-1}_{id} + c_1 r_1(p_{\text{best}}_{id} - x^{k-1}_{id}) + c_2 r_2(g_{\text{best}}_{id} - x^{k-1}_{id})
\]  
(24)

The location update formula is:

\[
x^{k}_{id} = x^{k-1}_{id} + v^{k-1}_{id},
\]  
(25)

where \(v^{k}_{id}\) is the d-dimensional component of the flying velocity vector of particle i at the kth iteration. \(x^{k}_{id}\) is the d-dimensional component of the position vector of particle i in the kth iteration. \(c_1\) and \(c_2\) are acceleration constants that are used to adjust the maximum step length for learning. \(r_1\) and \(r_2\) are two random functions with values ranging from 0 to 1, which are used to increase the randomness of the search. \(w\) is the inertial weight, which is a non-negative number and is used to adjust the search range of the solution space. The formula used to update the particle velocity consists of three parts, where the first part is the previous particle velocity; the second part is the “cognition” part,
which represents the thinking of the particle itself and can be understood as the distance between the current position of particle “\(i\)” and its best position. The third part is the “social” part, which represents the information sharing and cooperation among the particles, and can be understood as the distance between the current position of particle “\(i\)” and the best position for the group. The algorithm flow chart is shown in Fig. 19.

Based on the analysis and modeling above, the energy consumption optimization problem of the loader can be simplified as follows:

\[
\begin{aligned}
\min & f(X) \\
\text{st} & g_i(X) \geq 0, \quad i = 1, 2, 3, \ldots, n
\end{aligned}
\]  

(26)

where \(f(X)\) is the function that optimizes the objective in the solution process; \(g_i(X)\) are all the constraint functions for the optimization object during the optimization process; and \(X\) represents the optimization variables.

During the L-shaped operation of the loader, with the exception of the excavation section and the starting stage, the gearboxes in the other working sections are in either second or third gear. Second, when we consider that the first gear ratio must meet the requirements of high-power conditions, including the climbing angle, rapid acceleration and insertion requirements, the third gear reduction ratio must meet the highest vehicle speed requirement, the second gear ratio is used as the optimized variable, and the single cycle power consumption is the optimization goal. The objective function is then established as follows:

\[
\min E(i_2) = \int_0^T P\eta dt
\]

(27)

The influence of the optimized transmission ratio on the shift smoothness for the entire vehicle is an important factor for determination of the constraint conditions for the transmission ratio, and the fast response characteristics of the motor can just overcome the difficulty in shifting caused by the excessive transmission ratio.\(^{30}\) According to the gear shift strategy formulated in the gearbox module, when the motor peak speed constraint is taken into consideration, the motor speed at the loader’s gear switching point cannot exceed the peak speed, and the constraint conditions for the optimization variables are:

\[
\frac{n_{e1}}{n_{max}} < i_2 < \frac{n_{max} n_{i3}}{n_{e}},
\]

(28)

where \(n_e\) is the motor’s rated speed; and \(n_{max}\) is the peak motor speed.

In the optimization algorithm, the number of particle swarms is eight; the number of iterations is 100; the allowable error range is 0.001; the number of inertial weight factors is 0.6 and the acceleration constant is 0.8. Through iteration of the optimization algorithm, the optimal value for the second gear transmission ratio was found to be 1.338 and the power consumption of a single cycle operation was 0.2329 kW/h. Figure 20 shows the convergence of the solution objective during the optimization iteration process. Convergence was achieved at approximately 23 iterations.

**Simulation**

A backward simulation was performed on the motor and charts for comparison of the motor operating point distributions before and after optimization are shown in Fig. 21. Figure 21 shows that the motor operating points before and after optimization gradually move from low efficiency to higher efficiency, which then
reduces the power consumption of the loader operating cycle.

To compare the changes in the motor efficiency before and after optimization more intuitively, Fig. 22 shows the changes in motor efficiency over time. Figure 22 shows that the efficiency of the motor after optimization is higher than that before optimization during almost the entire cycle, particularly during the loader acceleration period, and this represents further evidence that the optimization process can improve the energy conversion efficiency.

Integration of the power spectrum before and after optimization allows a comparison of the energy consumption before and after optimization to be obtained, as shown in Fig. 23. It is obvious that as time passes, the energy consumption gap between the results before and after optimization broadens, and the energy consumption after optimization is lower than that before optimization.

A comparison of the performance of the loaders before and after optimization is shown in Table 4. The table shows that after optimization, the gearbox reduction ratio has decreased, and the amount of power consumed in one operating cycle decreases to 0.2329 kW·h from 0.2376 kW·h, representing a reduction by approximately 1.98%. In addition, the number of operating cycles for the loader under battery operation in the SOC healthy state increases from 576 to 587, representing an increase of approximately 1.91%.

Conclusions
In this paper, a loader power system model has been constructed and use of the PSO algorithm has been
proposed to optimize the loader after study of the optimization and matching of the power system parameters of the battery underground loader. Conclusions are drawn as follows.

(1) The optimal loader operating point has been determined through analysis of the power response characteristics of the motor under various operating conditions. The peak power and rated speed that correspond to this point not only meet the power requirements of the three short-term operating conditions, but also can ensure a specific working efficiency for the loader. At the same time, the laws and characteristics of several commonly used power battery underground loaders were also obtained under various working conditions. From the perspective of the unique working conditions of the loader, the applicability of the LiFePO4 battery to the battery underground loader is confirmed.

(2) Based on the research results reported here, the power train and battery parameters of the battery underground loader have been optimized and matched. After the parameters have been matched, the loader’s rated power can be reduced and its power endurance requirements can be met.

(3) Based on the developed model, the particle swarm algorithm was used to optimize the operating conditions for the drive motor. The results showed that the transmission ratio decreases after optimization, and the entire vehicle model saves approximately 1.98% of the total power in a single cycle of the model, while the number of cycles also increased by approximately 1.91% when the battery was in a healthy state. These results can serve as a reference for theoretical research in fields related to loaders.

(4) The PSO algorithm can easily be trapped into local optimization and future work will thus focus on combining PSO with other algorithms, e.g., evolutionary algorithms, fuzzy logic, biological intelligence and other methods or strategies, to achieve better optimization performance.

**Author contributions**

Data curation, S.Y.; Investigation, X.L.; Methodology, S.Y. and L.Z.; Project administration, Z.Y.; Writing – original draft, S.Y.; Writing – review and editing, S.Y.

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**Table 4. Loader performance comparison before and after optimization.**

| Variable               | Second gear ratio | Power consumption (kW·h) | No. of cycles |
|------------------------|-------------------|--------------------------|--------------|
| Before optimization    | 1.94              | 0.2376                   | 576          |
| Optimized              | 1.34              | 0.2329                   | 587          |
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