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Research Article

Modeling and Optimization of Soft Start-Up for Hydroviscous Drive Applied to Scraper Conveyor

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To improve the soft start-up performance of a scraper conveyor under different working conditions, the mathematical model of the torque for controllable starting transmission was established. The influences of start-up time, load values, and moment of inertia on the soft start-up characteristics of a scraper conveyor are analyzed. Based on the analytic hierarchy process (AHP), the new evaluation system of soft start-up optimization for hydroviscous drive applied to a scraper conveyor is proposed. Through the joint simulation platform of MATLAB and Isight, the two-parameter control model for soft start-up time is established using the method of experimental design and simulated annealing algorithm. The optimal start-up time under different conditions is determined, and soft start-up is optimized. The results show that with increasing start-up time, the objective function value of soft start-up performance decreases first and then increases. Under different flywheel inertia and load conditions, there is an optimal start-up time that minimizes the objective function for better soft start-up performance. The optimal start-up time decreases with increasing load, and the optimal start-up time decreases monotonically with the input flywheel inertia. This research provides a new method and theoretical basis for the modeling and performance optimization of soft start-up for hydroviscous drive applied to a scraper conveyor.

1. Introduction

Scraper conveyors often encounter overload, chain clamping, and chain breaking during operation. It is necessary to protect the transmission system during shutdown. Therefore, scraper conveyors are started under different loads, and this puts forward higher requirements for soft start-up technology. The hydraulic-viscous drive (HVD) with controllable starting transmission can make full use of motor maximum peak torque and the input moment of inertia to realize scraper conveyor soft start-up function. The output torque and speed of the drive system are controlled by the HVD. In the process of soft start-up, the HVD oil pressure control and start time have significant influence on the soft start-up performance. Therefore, it is necessary to optimize the soft start-up of scraper conveyors in order to obtain the optimal start-up time and control scheme under different working conditions.

Many researchers have analyzed the dynamic characteristics of scraper conveyors during start-up. Due to difficulty starting scraper conveyor driving systems, a soft start system was researched and developed [1]. Based on ADAMS, a virtual prototype scraper conveyor model is built, and a start, brake, rated, and abnormal load dynamic analysis is carried out [2]. With full loading, the dynamic characteristics of a scraper conveyor were simulated under direct start, controlled start, freewheel, brake, and restart conditions [3]. Through the scraper conveyor system dynamics, the test conditions were tested [4]. It is best to reduce the starting fluctuant load by controlling the conveyor starting types [5].

Meanwhile, some relative research works with hydroviscous drives are presented. The dynamic transmission of the oil film in the soft start process of a hydroviscous drive between the friction pairs with the consideration of surface roughness was analyzed [6]. The influence of groove structure parameters on shear torque was analyzed [7]. Meng studied the variations in the oil film load capacity, temperature, and the torque generated by the oil film during the starting process [8]. Meng and Hou also developed equipment and carried out a number of experiments to reveal the effect of working oil temperature, load, and starting time on a hydroviscous drive speed-regulating start [9]. Chen et al. obtained that the nonlinearity of the pressure performance curve is one key cause of the poor start-up smoothness [10]. Cui et al. studied the influence of the fluid-inertia item on the HVD dynamic transmission [11]. The Isight integrated optimization design platform of friction pairs in HVD was built, and the groove structure parameters were optimized [12].

In addition, the research on start-up performance optimization mainly focuses on hydraulic torque converters and automobiles. To study the influence of double arc oil groove parameters on oil film torque in hydroviscous drives, Cui et al. built a numerical simulation and parameterized analyzing platform [13]. Two different collaborative optimization models of a gear reducer are built separately in the multidisciplinary design optimization software Isight [14]. With AMESim integrated into the Isight platform, Ma et al. analyzed the parameters of a shock absorber model [15]. Yang et al. carried out a multiobjective optimization for improving the behavior of handling and ride comfort [16]. Shi and Sun presented an automatic optimization strategy by integrating four pieces of software in the Isight platform [17]. Xiao et al. carried out the turning test of stainless steel by using the central composite surface design of response surface method [18]. An optimal mechanism is obtained by an optimization method combining ANSYS with MATLAB to accomplish the multiobjective optimization of the flexure hinge mechanism [19]. Based on the optimization method, a study is performed for different thickness of plate to obtain the corresponding roller velocity [20].

However, at present, with the increase of carrying capacity of the scraper conveyor, it is difficult to meet the start-up requirements under different working conditions with fixed start-up time. In order to improve the soft start-up performance and reduce the start-up impact and sliding loss power of the scraper conveyor under different loads, the optimal start-up time under different loads is determined through the establishment of soft start-up optimization evaluation system and two-parameter control model of soft start-up time.

Taking the HVD soft start-up process for a scraper conveyor as the research object, the mathematical model of the controllable starting transmission torque and the evaluation system for soft start-up optimization are established. The impact, sliding friction work, and utilization rate of the inertial start-up are taken as evaluation indexes, respectively, to analyze the influence of start-up time, moment of inertia, and load on the start performance. Using the optimization method of experimental design and simulated annealing algorithm, the response surface model of soft start-up time taken into account to the variables of load value and flywheel inertia is established, and the optimal start-up time under different conditions is finally determined, which can realize performance analysis and design optimization of the soft start-up for the scraper conveyor.

Thus, this paper proposes an optimization scheme of soft start-up time using the joint simulation of MATLAB and Isight to enhance the soft start-up performance of a scraper conveyor. This paper is organized as follows. Section 2 presents the mathematical model of the controllable starting transmission torque. In Section 3, the evaluation systems for soft start-up performance are established. In Section 4, the influences of start-up time, load values, and moment of inertia on the soft start-up characteristics of a scraper conveyor are analyzed and a two-parameter control optimization model for soft start-up time is constructed. Finally, conclusions are drawn in Section 5.

2. Mathematical Model

The scraper conveyor can be soft-started using a controllable starting transmission. The mathematical torque models for electromechanical-hydraulic coupled systems are established. The matching relationship of the driving motor, HVD, and scraper conveyor in the soft start-up process is analyzed for the best soft start-up scheme under different working conditions and to obtain the optimal start-up time.

2.1. Torque of the Scraper Conveyor. In the scraper conveyor torque model, the load distribution, running resistance, and resistance coefficients are analyzed [21]. According to the empirical equation, the relationship between load torque T_{L} and sprocket speed ω_{L} during scraper conveyor start-up is as follows:

$$\begin{aligned} T_L &= J\dot{\omega}_{\mathrm{L}} + Wr \\ &= J\dot{\omega}_{\mathrm{L}} + 1.21\left[\left(q_a + q_b\right)gL_1\mu_1 + q_a g\mu_2\left(L - L_1\right) + q_a gL\mu_2\right]r \\ &= J\dot{\omega}_{\mathrm{L}} + 1.21\left[\left(q_a + q_b\right)gL_1\mu_1 + \left(2q_a gL - q_a gL_1\right)\mu_2\right]r, \end{aligned} \tag{1}$$

where W is the running resistance; r is the sprocket radius; J is the load equivalent moment of inertia $J = (q_a^2 L + q_b L_1)r^2$; q_a is the unit length mass of the scraper and scraper chain; q_b is the unit load distribution; L is the laying length of the scraper conveyor; and L_1 is the coal length of the scraper conveyor.

By using the Goodell test, the friction coefficient between the scraper chain and chute can be obtained as $\mu_{\mathrm{ss}} = 0.28 - 0.0375\mathrm{V}$; the coefficient of friction between coal and chute is $\mu_{\mathrm{cs}} = 0.39 - 0.00625\mathrm{V}$; the coefficient of dynamic friction between coal and coal is $\mu_{\mathrm{cc}} = 0.84$. Therefore, the load side equivalent resistance coefficient μ_1 and the no-load side equivalent resistance coefficient μ_2 are

$$\begin{cases} \mu_1 = \left[\dfrac{q_a\mu_{\mathrm{ss}} + q_b\mu_{\mathrm{cs}} + \left(\mu_{\mathrm{cc}} + \mu_{\mathrm{cs}}\right)\lambda N}{\left(q_a + q_b\right)}\right], \\ \mu_2 = \mu_{\mathrm{ss}}, \end{cases} \tag{2}$$

where V is the chain speed; λ is the lateral pressure coefficient; and N is the lateral pressure of coal.

2.2. HVD Torque. The structure of the HVD friction pair is shown in Figure 1. The braking torque of friction pairs in HVD during soft start-up consists of two parts: oil film shear torque T_{h} and rough contact torque T_{c}. Because there are double arc oil grooves on the surface of the friction disc, the effective area coefficient ψ is defined as the ratio of the area of nonoil grooves to the total area, and the contact area ratio B is fully taken into account. Then, the braking torque between friction pairs during soft start-up is as follows [11]:

$$T_{\mathrm{ch}} = n(1-B)\psi T_{\mathrm{h}} + nB\psi T_{\mathrm{c}},$$
$$T_{\mathrm{h}} = \mu\int_0^{2\pi}\int_{R_1}^{R_2} r^3\frac{\omega}{h}\,dr\,d\theta = \frac{\pi\mu\omega}{2h}\left(R_2^4 - R_1^4\right), \tag{3}$$
$$T_{\mathrm{c}} = f\int_0^{2\pi}\int_{R_1}^{R_2} r^2 p_{\mathrm{c}}\,dr\,d\theta = \frac{2\pi f p_{\mathrm{c}}}{3}\left(R_2^3 - R_1^3\right),$$

where n is the number of friction pairs; ω is the difference in rotation speed between static and dynamic friction plates; R_1 and R_2 are the inner and outer diameters of the friction pair, respectively; μ is the dynamic viscosity of lubricating oil; h is the oil thickness; f is a friction coefficient $f = 0.13 - 0.008\ln\omega$; and p_{c} is the pressure when two rough surfaces come into contact [22].

The contact area ratio of the friction pair is defined as B. The friction pair surface roughness obeys a Gaussian probability distribution, so the ratio of real to nominal contact area is [22]

$$B = \frac{\pi^2(\eta R\sigma^*)^2}{2}\left(1+H^2\right)\operatorname{erfc}\left(\frac{H}{\sqrt{2}}\right) - \sqrt{\frac{2}{\pi}}H\exp\left(-\frac{H^2}{2}\right), \tag{4}$$

where η, R, and σ^* are the peak point density of the rough surface, the radius of curvature, and the mean variance of peak height, respectively, and H is the ratio of film thickness, $H = h/\sigma$.

Greenwood and Tripp built a GT model based on a G-W model [23] and derived the pressure of contact between two rough surfaces p_{c}:

$$p_{\mathrm{c}}(H) = \begin{cases} 4.4086\times10^{-5}K'E'(3-H)^{6.804}, & H\le 3,\\ 0, & H>3, \end{cases} \tag{5}$$

where $K' = 8\sqrt{2}/15\pi(\eta R\sigma^*)^2\sqrt{\sigma^*/R}$ and E' is the equivalent elastic modulus of a friction pair.

2.3. Torque of Planetary Transmission. The schematic figure of the planetary gear transmission in HVD is shown in Figure 2. The dynamic equation is as follows:

$$\begin{aligned} J_{\mathrm{S}}\frac{d\omega_{\mathrm{S}}}{dt} &= T_{\mathrm{t}} - F_{\mathrm{S}}r_{\mathrm{R}},\\ J_{\mathrm{C}}\frac{d\omega_{\mathrm{C}}}{dt} &= F_{\mathrm{C}}r_{\mathrm{C}} - T_{\mathrm{L}},\\ J_{\mathrm{R}}\frac{d\omega_{\mathrm{R}}}{dt} &= F_{\mathrm{R}}r_{\mathrm{R}} - T_{\mathrm{ch}},\\ F_{\mathrm{S}} : F_{\mathrm{R}} : F_{\mathrm{C}} &= 1:1:-2,\\ 2r_{\mathrm{C}} &= r_{\mathrm{R}} + r_{\mathrm{S}}, \end{aligned} \tag{6}$$

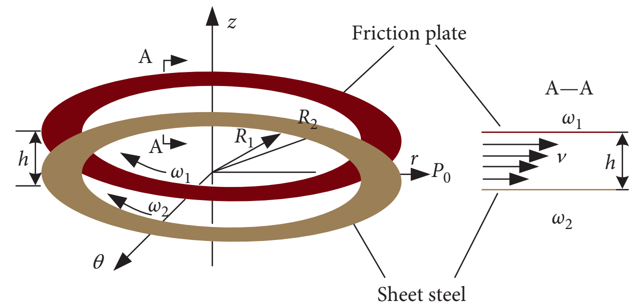

Figure 1: Structure of friction pair.

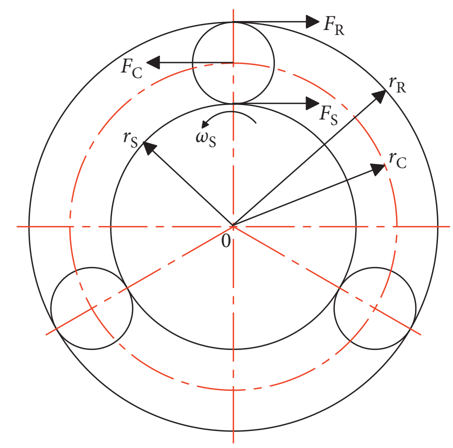

Figure 2: Schematic of planetary gear transmission.

where the subscripts S, R, and C represent the sun wheel, inner gear ring, and planet carrier, respectively, J is the moment of inertia, ω is angular velocity, and T_{t} is the solar wheel input torque.

3. Evaluation System

As the power transmission system for a scraper conveyor, the controllable starting transmission has the very important functions of soft start-up with load and inertial start with maximum motor torque. The complexity of working conditions and uncertainty of scraper conveyor load during start-up put forward higher requirements for the controllable starting transmission soft start-up process. At present, there is no uniform regulation on the evaluation methods and indices of the soft start-up process. This study mainly evaluates the soft start-up process from three aspects: reducing the thermal load of the friction plates, improving the inertial start-up utilization rate, and reducing the start-up impact.

3.1. Evaluation Index. In the process of soft start-up for the scraper conveyor, the sliding friction work produced by the soft start-up has a significant influence on the thermal load of the HVD. Therefore, the sliding friction work can be used as an evaluation index for soft start-up. At the same time, the driving motor provides large load and inertial moments for the scraper conveyor through the HVD, and the impact and utilization rate of inertia start-up can be used as evaluation indices.

Considering the stability, rapidity, and reliability of the HVD soft start-up process, the following indices are evaluated.

3.1.1. Impact Degree. The impact degree in the HVD mainly refers to the rate of angular acceleration change for the moving friction plates with the internal gear ring from dynamic to static. Its mathematical expression is as follows [24]:

$$j = \frac{da}{dt} = \frac{d^2\Delta\omega}{dt^2} = \frac{1}{J_{\mathrm{R}}}\frac{d\left(T_{\mathrm{ch}} - T_{\mathrm{R}}\right)}{dt}. \tag{7}$$

According to the equation, the impact degree is mainly determined by the rate of clutch output torque change, and the clutch torque change is mainly determined by the load scraper conveyor torque change. Therefore, the load, soft start-up speed, and start time have a significant influence on the impact degree. According to the literature [25], the recommended impact degree in China is $17.64\,\mathrm{m/s^3}$, whereas in Germany, it is $10\,\mathrm{m/s^3}$ for automobiles. Therefore, the start-up time should not be too small on the premise of satisfying the load start-up.

3.1.2. Sliding Friction Work. Sliding friction work refers to the work consumed by the thermal load generated from the sliding transfer torque of the static and dynamic friction plates during the soft start-up process. Its mathematical expression is as follows:

$$W_{\mathrm{C}} = \int_{t_1}^{t_2} T_{\mathrm{ch}} \cdot \Delta\omega\, dt, \tag{8}$$

where T_{ch} is the friction torque transferred by the HVD, $\Delta\omega$ is the angular velocity difference between dynamic and static HVD friction plates, and t_1 and t_2 are the moments when the clutch static and dynamic friction plates start sliding and when the HVD friction plates become synchronous, respectively.

The HVD transmits torque through the shear oil film and rough surface contact. Sliding friction increases the temperature of the static friction steel sheet and paper-based dynamic friction plates and accelerates their wear and warpage. Therefore, the sliding time should be shortened to realize quick HVD combination.

3.1.3. Utilization Rate of Inertia Start-Up. The utilization rate of inertia start-up refers to the percentage of torque provided by the motor inertia and flywheel at the driving end in the driving torque. The index represents the starting capability of the controllable starting transmission. The mathematical expression is

$$\eta = \frac{J_0\dot{\omega}_n}{T_t} = \frac{iJ_0}{T_{\mathrm{ch}}}\frac{d\omega_n}{dt}, \tag{9}$$

where J_0 is the input equivalent moment of inertia, ω_n is the driving motor speed, and i is the transmission ratio.

It can be seen that the utilization ratio of inertial start-up is mainly related to the input equivalent moment of inertia, start-up time, and load. Therefore, increasing the moment of inertia and shortening the start-up time effectively improve the utilization ratio for inertial start-up.

Through the analysis of the above three evaluation indices, we can see that the start-up time directly affects the quality of the soft start-up process. When the start-up time is long, the clutch combination process and output torque are stable and the impact is small, but the utilization rate of inertia start-up is low, and the starting capability decreases under heavy load conditions. When the sliding friction work increases, the temperature of the friction disc increases significantly, this affects the output torque and component reliability. Load and the input equivalent moment of inertia affect the HVD evaluation index at the same time, so start-up time, scraper conveyor load (i.e., coal-laying length at start-up time), and input equivalent moment of inertia (i.e., flywheel inertia) are taken as parameter variables to optimize the soft start-up quality for HVD.

3.2. Optimization Model. According to the analysis of factors influencing soft start-up optimization, soft start-up is carried out based on the s-type velocity curve of the scraper conveyor. Start-up time T, flywheel moment of inertia J_0, and coal-laying length of the scraper conveyor L_1 can be selected as the variables for optimal design.

A multiobjective optimization method is used to optimize the soft start-up process, and its evaluation indices are impact degree, sliding friction work, and starting capability. The multiobjective function is solved by the method of linear weighted sum, and the single-objective evaluation function S is constructed. Its expression is as follows:

$$S = \omega_1 j + \omega_2 W_{\mathrm{C}} + \omega_3\eta, \tag{10}$$

where ω_1, ω_2, and ω_3 are weighting coefficients for impact degree, sliding friction work, and starting capability.

In calculation, it is necessary to normalize the parameters linearly since the dimension and magnitude of each target are different:

$$\begin{cases} j' = \dfrac{j}{[j]}, \\ W'_{\mathrm{C}} = \dfrac{W_{\mathrm{C}} - W_{\mathrm{C\,min}}}{W_{\mathrm{C\,max}} - W_{\mathrm{C\,min}}}, \end{cases} \tag{11}$$

where j' is the relative value of the normalized impact degree; $[j]$ is the allowable value of impact degree; W'_{C} is the relative value of the normalized sliding friction work; and $W_{\mathrm{C\,min}}$ and $W_{\mathrm{C\,max}}$ are the minimum and maximum values of the variation range of sliding friction work, respectively.

The value of starting capability reflects the quality of the soft start-up process. The larger the value is, the better the start-up performance will be. To achieve a unified optimization objective, the relative value of starting capability is defined as

$$\eta' = 1 - \eta. \tag{12}$$

Therefore, the normalized optimization objective function is

$$\min S = \min\left(w_1 j' + w_2 W'_{\mathrm{C}} + w_3 \eta'\right). \tag{13}$$

The design variable value is

$$\text{s.t.} \quad \begin{aligned} &2 \le T \le 11, \\ &0 \le J_0 \le 100, \\ &0 \le L_1 \le 300. \end{aligned} \tag{14}$$

3.3. Weight of Evaluation Index. The above three evaluation indices are not equally important in the soft start-up process. They can be coordinated according to the matching characteristics of the controllable starting transmission and scraper conveyor. Generally, the weight of the impact degree can be increased when the steady start of load is more important. The weight of sliding friction work should be increased appropriately when the reliability of the HVD is emphasized. The utilization rate of inertia start-up can be increased appropriately when the load start performance is emphasized under heavy start conditions.

This research will determine the weight of each evaluation index based on the analytic hierarchy process (AHP) and quantitatively analyze the optimum performance for the soft start-up process [26]. The AHP is more suitable for target systems with a hierarchical and staggered evaluation index. The main steps of the AHP are as follows: (1) analyzing and establishing the hierarchical structure model; (2) constructing all judgment matrices in each level and calculating the weight of each index; and (3) conducting a consistency test.

3.3.1. Hierarchy Structure Model. Combined with the optimization model, the evaluation indices are discussed, and a hierarchical structure model is established for the optimization of soft start-up as shown in Figure 3.

3.3.2. Weight Calculation. From Figure 3, we see that the hierarchical structure reflects the relationships among the indicators. However, the proportion of each evaluation index in the target measurement is different. The 1–9 scale of professor Saaty [26] is used to construct the judgment matrix. The relative importance of indices is determined by the 9/9~9/1 scale method, and the meaning of each scale is shown in Table 1.

According to the analysis of load soft start-up, the relative importance of the three evaluation indicators is reasonably sorted. The relative importance between the two evaluation indicators is evaluated according to the expert scoring principle and quantified according to the scale meaning of Table 1. When the stability and rapidity of start-up performance are emphasized, the decision-making judgment matrix $\mathbf{J}$ is established as shown in the following equation:

$$\mathbf{J} = \begin{array}{c} \\ \eta' \\ W'_{\mathrm{C}} \\ j' \end{array} \begin{array}{c} \begin{array}{ccc} \eta' & W'_{\mathrm{C}} & j' \end{array} \\ \begin{bmatrix} 9/9 & 9/6 & 7/9 \\ 6/9 & 9/9 & 4/9 \\ 9/7 & 9/4 & 9/9 \end{bmatrix} \end{array}. \tag{15}$$

3.3.3. Consistency Test. The judgment matrix $\mathbf{J}$ can objectively reflect the difference in the magnitude of each index's influence on the other, but there is inevitably some inconsistency among these values. Therefore, the consistency test is needed to determine whether the matrix is reasonable or not. The quantitative indicators to measure the consistency of the judgment matrix are consistency index (CI), average random consistency index (RI), and consistency ratio (CR) [27].

The maximum eigenvector of the judgment matrix $\mathbf{J}$ is $\lambda_{\max} = 3.0026$, and its corresponding eigenvector is as follows: $\mathrm{W} = \left[\, 0.5562 \;\; 0.3522 \;\; 0.7528 \,\right]$. When the order of judgment matrix n is 3, the average random consistency index RI is 0.58.

So, we get

$$\begin{cases} \mathrm{CI} = \dfrac{\lambda_{\max} - n}{n - 1} = 0.0013, \\[2ex] \mathrm{CR} = \dfrac{\mathrm{CI}}{\mathrm{RI}} = 0.0022 \ll 0.1. \end{cases} \tag{16}$$

When $\mathrm{CR} < 0.1$, the inconsistency of judgment matrix is acceptable. Therefore, the judgment matrix $\mathbf{J}$ satisfies the consistency requirement, and the relative weights of the eigenvector W corresponding to the maximum eigenvalue are η', W'_{C}, and j' in turn.

4. Analysis of Optimization Results

4.1. Optimization Process. The objective of soft start-up optimization for a controllable starting transmission is to optimize the start-up within the range of parameter variable design without exceeding the allowable evaluation index value. According to the analytical expression, the relationship between objective function and design variable is analyzed by integrating multiple simulation platforms, and the optimal objective function value is obtained to realize the optimal design for parameter variables.

Taking the controllable starting transmission torque mathematical model as the research object, using MATLAB to calculate each index of the soft start-up process, combined with the Isight optimization simulation platform, the parametric model for objective function, design of experiment (DOE), response surface model (RSM), and simulated annealing optimization algorithm are established. Through this platform, the influence of design variables on soft start-up performance is analyzed, and the parameters are optimized.

To study the optimization of the scraper conveyor soft start-up process, three evaluation indices and three parameter variables are proposed. The experimental design of parameter variables is carried out using a limited number of

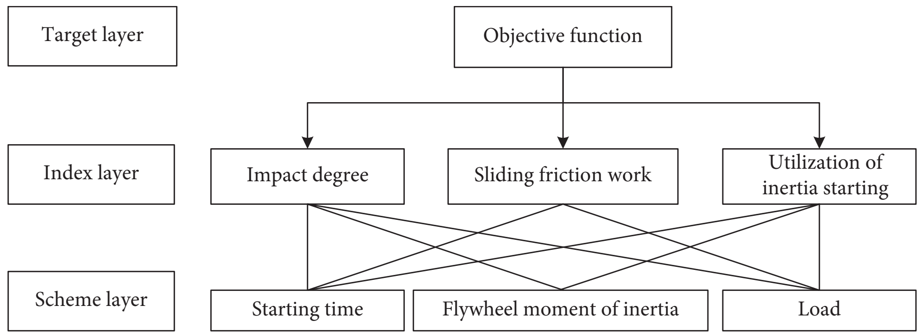

Figure 3: Hierarchy structure model.

sample points, and the parameter tables are constructed by combination within the allowable range. In the MATLAB cycle calculation module, all kinds of combined models are calculated. After data extraction, the database of impact degree, sliding friction work, utilization rate of inertia start-up, and objective function of HVD under different parameter combinations can be obtained, and the main and interaction effect analysis for each parameter variable can be carried out. Then, the approximate response surface model for parameter variables and objective function is constructed by regression, fitting, and interpolation. The optimal start-up time of the objective function on the approximate response surface is obtained by optimizing the approximate model. The integrated optimization design process is shown in Figure 4.

4.2. Results and Discussion. The soft start-up performance of the scraper conveyor controllable starting transmission is mainly based on the analysis of three influencing factors: load value, start-up time, and flywheel inertia. To accurately analyze the main and interaction effects of the three factors on start-up performance, 200 horizontal test data of the three variables are constructed by the Latin square test method. Soft start-up performance analysis and optimization design are realized by iterating the program repeatedly through the integrated optimization design platform of Isight and MATLAB.

4.2.1. Pareto Figure. A Pareto figure reflects the percentage of contribution of all parameter variables to each response in the model after sample fitting. It is characterized by the influence of independent variables on dependent variables, such as the linear correlation, square correlation, and interaction response of independent variables.

Figure 5 is a Pareto figure showing the effect of start-up time, load value, and flywheel inertia on the soft start-up performance objective function and each evaluation index. The blue bar represents a positive effect, indicating that with increasing parameter variables, the evaluation index also increases. The red bar represents the negative effect, indicating that the evaluation index decreases with increasing parameter variables.

From the analysis of the objective function (Figure 5(a)), the quadratic effect of soft start-up time has the greatest correlation (39.75%). The linear positive effect of load and start-up time and the positive effect of interaction between load and start-up time are, respectively, 28.65%, 14.32%, and 10.42%. The larger the parameter variable is, the bigger the

Table 1: Scale of judgment matrix and its meaning.

Scale	Meaning
9/9	The comparison of two elements has the same importance
9/8	The two elements are compared at the same and slightly more important intermediate values
9/7	The former is slightly more important than the latter
9/6	The two elements are compared at the slightly more important and more important intermediate values
9/5	The former is more important than the latter
9/4	The two elements are compared at the more important and obviously more important intermediate values
9/3	The former is obviously more important than the latter
9/2	The two elements are compared at the obviously more important and strongly more important intermediate values
9/1	The former is strongly more important than the latter

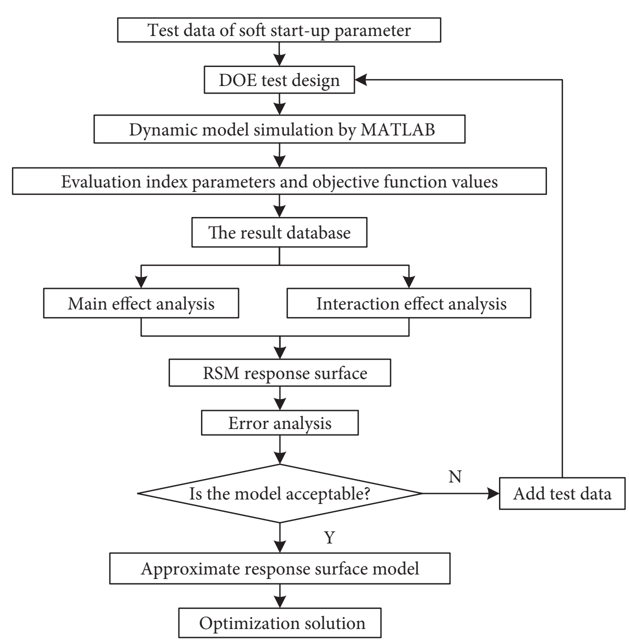

Figure 4: Flowchart of integrated optimization design.

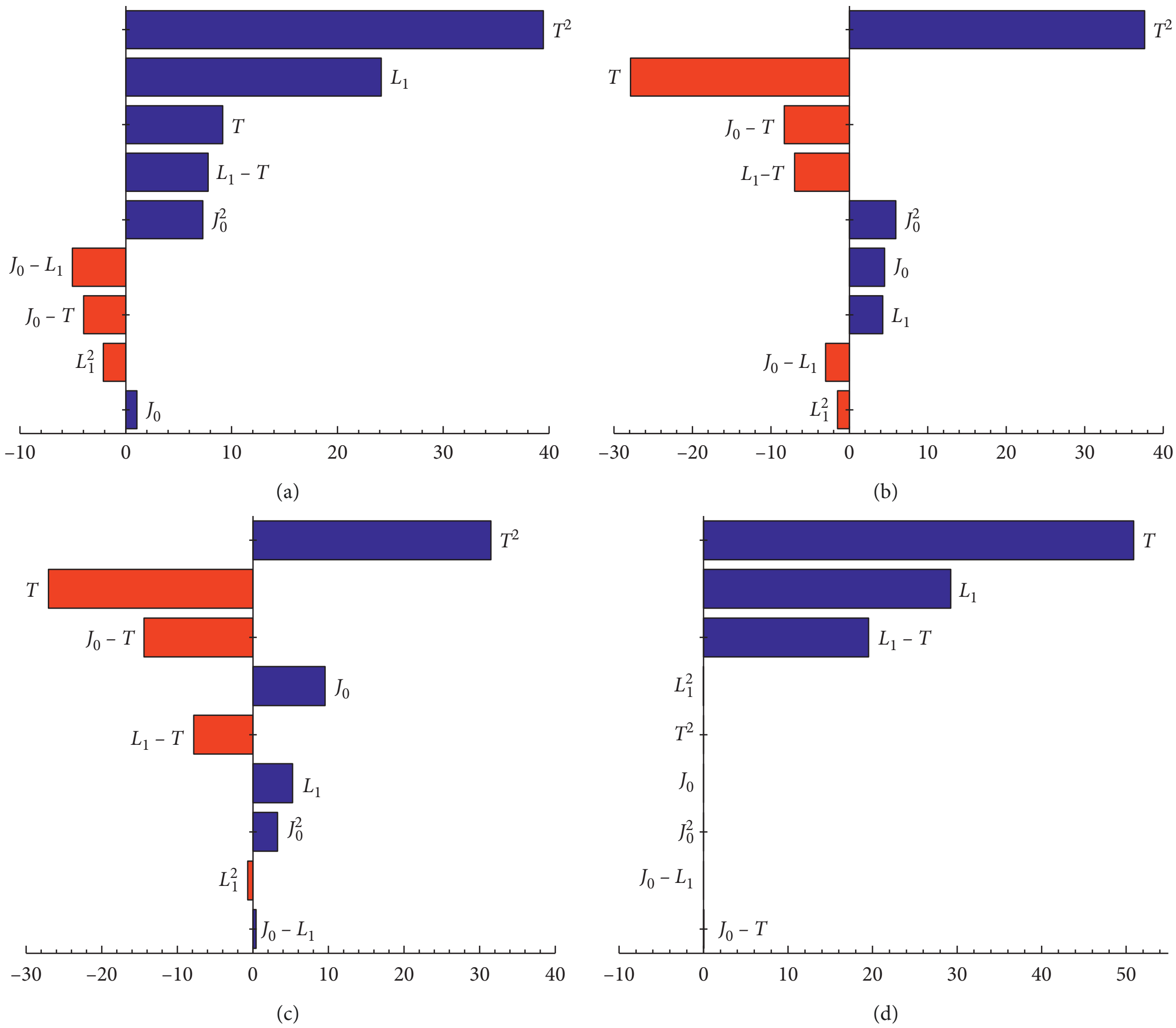

FIGURE 5: Pareto figures: the effect on (a) the objective function, (b) the impact degree, (c) the utilization rate of inertia start-up, and (d) the sliding friction.

objective function value and the worse the soft start-up performance will be. The results show that the start-up time has the greatest impact on the objective function of scraper conveyor's soft start-up performance, and the optimization of start-up time should be emphasized.

According to the analysis of Figures 5(b) and 5(c), with increasing start-up time, the evaluation index is negative. That is, the impact degree decreases, and the starting capability decreases. The load and flywheel inertia are positive effects, indicating increased impact degree and starting capability. From Figure 5(d), it can be concluded that the factors influencing sliding friction work are only related to start-up time and load, and both are positive effects. With the increase in start-up time and load, the sliding friction work increases.

Therefore, the impact degree, starting capability, and sliding friction work of the evaluation index are contradictory, and the optimization results are not a linear superposition of the optimal values of the three. To obtain the optimal solution of the objective function, it is necessary to analyze each influencing factor.

4.2.2. Main Effect Analysis. The main effect figure is the relationship between parameter variables and evaluation indices. In the experimental design, the slope of the parameter variable in the main effect figure is consistent with the contribution of the Pareto figure variable. The value of the main effect is expressed as the influence of the parameter variable on the response of the objective function.

Figure 6 shows the main effect of each parameter variable on the soft start-up performance objective function and each evaluation index. According to the figure of the objective function, with increasing start-up time, the objective function value tends to decrease first and then increase. That is, under the condition that the flywheel inertia and the load are fixed, the optimal start-up time value exists, and the average value of the objective function is the minimum when the start-up time is 5.5 s.

At different load levels, the average trend in the objective function value monotonically increases. With increasing load, the objective function increases, indicating that the soft start-up performance deteriorates under heavy load. However, when the flywheel inertia is at different levels, the

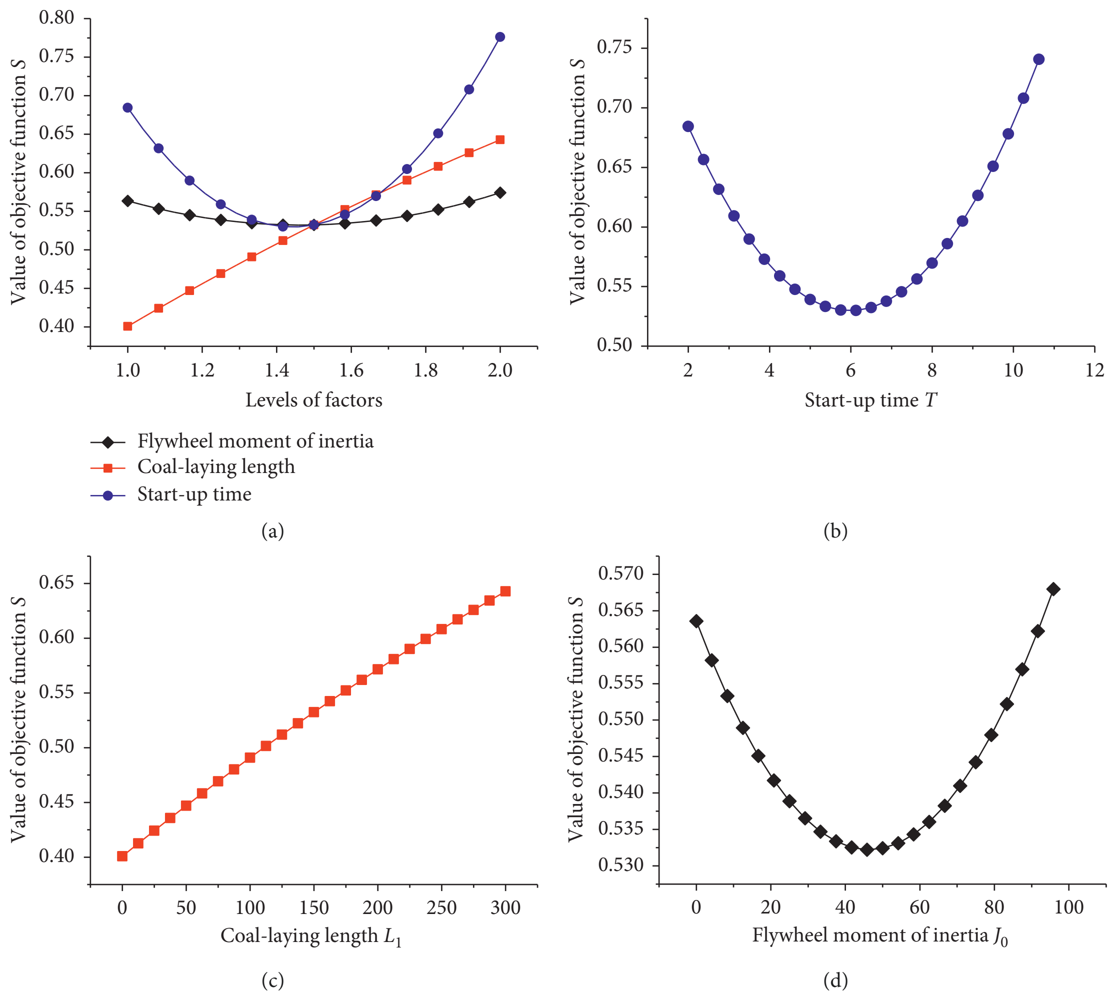

Figure 6: The main effect relationship between (a) the objective function and each evaluation index, (b) the objective function and start-up time, (c) the objective function and coal-laying length, and (d) the objective function and flywheel moment of inertia.

objective function value tends to decrease first and then increase. At the same time, the effect of start-up time on the objective function is the largest, followed by the load, and the flywheel inertia has the smallest effect.

4.2.3. Analysis of Interaction Effects. According to the main effect analysis, the interaction effect reflects the relationship and degree between the interaction of two parameter variables and the response of the objective function. In the interaction effect figure, if two lines are parallel, it means that there is no interaction. If the two lines are not parallel or cross, there is an interaction. The degree of nonparallelism reflects the strength of the interaction.

Figure 7 shows an analysis of the interaction effect for each parameter variable of the objective function. The black line indicates that the parameter variable takes a smaller value, and the blue line indicates that the parameter variable takes a larger value. In the interaction effect analysis figure for the three factors, the lines are not parallel, indicating that the interaction effect is relatively significant. In Figure 7(a), when the load is small, the response objective function changes obviously, which indicates that the interaction effect between load and start-up time is strong under light load. Similarly, in Figure 7(b), the longer the start-up time, the stronger the interaction effect between start-up time and flywheel inertia. As seen from Figure 7(c), the interaction effect curves intersect, which indicates that the interaction effect between load and flywheel inertia is stronger under heavy load.

4.3. Response Surface Model. Through the experimental design of soft start-up performance parameter variables and the analysis of the main and interaction effects of the objective function, it can be seen that start-up time, load, and flywheel inertia have different effects on start-up performance. To optimize the performance of hydroviscous soft start-up and obtain the optimal start-up time and scheme, it is necessary to construct an approximate response surface model of the objective function for each parameter variable.

The approximate response surface model is designed using polynomial functions, which can be first, second, third, and fourth order. The first to the fourth-order response surface approximation model was used to fit the sample data, and 10 sample points were randomly selected. The accuracy of

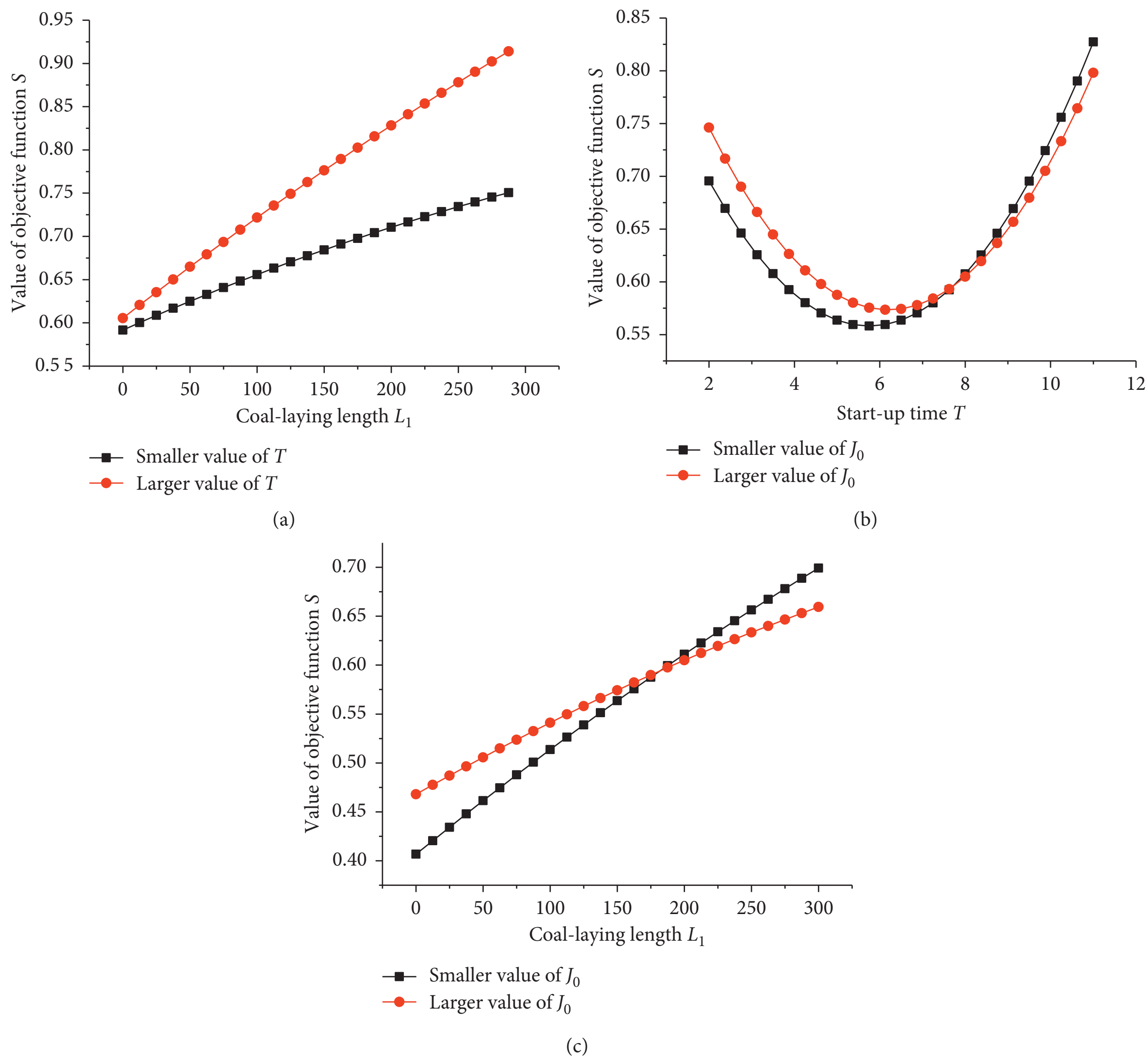

Figure 7: The interaction effect relationship between (a) the start-up time and coal-laying length, (b) the flywheel moment of inertia and start-up time, and (c) the flywheel moment of inertia and coal-laying length.

the model was analyzed by comparing the average, maximum, and root mean square error and the R^2 fitting degree. Finally, the approximate response surface model was determined and the optimal solution of the objective function was obtained. The results are shown in Table 2.

The R^2 fitting degree reflects the degree to which the model conforms to the actual response value. From the table, it can be seen that the response surface fitting of the ternary quartic regression equation has high reliability. Therefore, the response surface equation of the soft start-up performance objective function with respect to parameter variables is constructed as follows:

$$\begin{aligned} S = {} & 1.7638 - 0.8341T + 0.0007L_1 - 0.0017J_0 + 0.1821T^2 \\ & - 2.356\times10^{-6}L_1^2 + 0.00017J_0^2 + 4.68\times10^{-5}TL_1 \\ & - 5.78\times10^{-5}TJ_0 - 9.04\times10^{-7}L_1J_0 - 0.0167T^3 \\ & + 1.09\times10^{-8}L_1^3 - 4.46\times10^{-6}J_0^3 + 0.00055T^4 \\ & - 1.66\times10^{-11}L_1^4 + 3.8\times10^{-8}J_0^4. \end{aligned} \tag{17}$$

According to the response surface equation of the fitted objective function, the influence of start-up time, load, and flywheel inertia on soft start-up performance can be obtained, as shown in Figure 8. From Figure 8(a), it can be seen that the light load condition has better soft start-up performance compared with heavy load condition. When the load and flywheel inertia are fixed, the objective function decreases first and then increases with the increase in the start-up time. Therefore, the optimal soft start-up performance of the scraper conveyor can be obtained by optimizing start-up time under specific conditions.

Figure 8(b) shows that the objective function decreases monotonically with the decrease of load and decreases first and then increases with the increase of flywheel inertia. Figure 8(c) shows that the flywheel inertia and start-up time have optimal solutions to minimize the value of the objective function under fixed load. Thus, the optimal start time can be determined to improve the scraper conveyor soft start-up process under the combined influence of loads and flywheel inertia.

Table 2: Error analysis of RSM surface.

	Average error	Maximum error	Root mean square error	R^2 fitting
First order	0.113	0.193	0.123	0.884
Second order	0.096	0.437	0.152	0.826
Third order	0.04	0.11	0.046	0.972
Fourth order	0.028	0.071	0.037	0.982
Allowable value	<0.2	<0.3	<0.2	>0.9

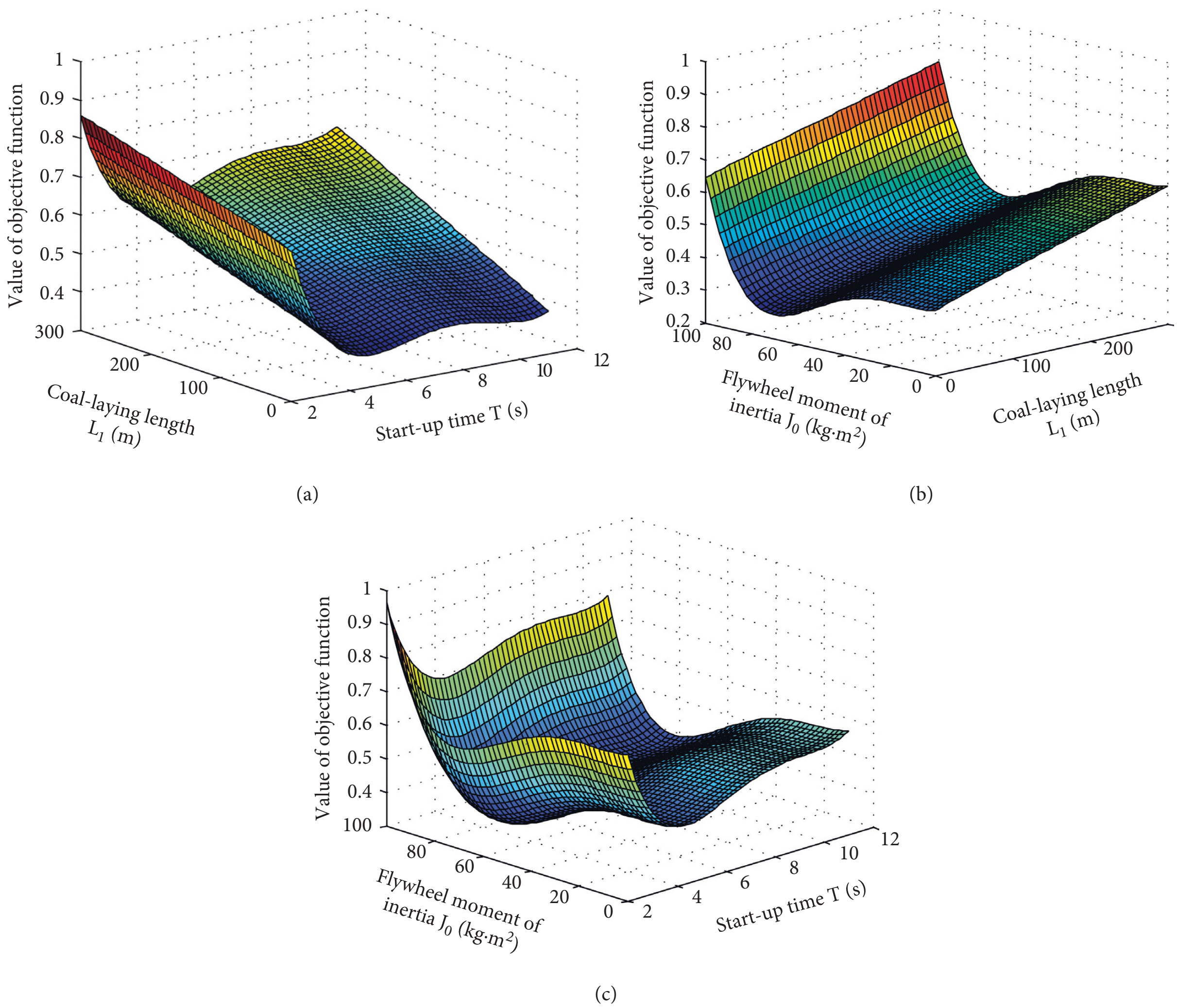

Figure 8: Response surface figures: the effect of (a) start-up time and coal-laying length on the objective function, (b) flywheel moment of inertia and coal-laying length on the objective function, and (c) flywheel moment of inertia and start-up time on the objective function.

4.4. Optimization of Start-Up Time. Through theoretical calculation and simulation analysis, it can be seen that the start-up time has an obvious effect on the start-up performance of the scraper conveyor. The optimal start-up time should be adjusted according to the load and flywheel inertia so as to optimize the soft start-up performance of the scraper conveyor.

When the flywheel inertia is fixed, the start-up time is analyzed and optimized, and the minimum objective function under different loads is determined. The optimization results are shown in Table 3. From the table, it can be seen that the optimized start-up time decreases with increasing load. The utilization rate of inertia torque increases with the decrease of start-up time, which is conducive to the performance of start-up. At the same time, the sliding friction work and impact degree increase, but both are within the allowable range.

When the load is full, the start-up time is optimized for different flywheel inertia values. The results are shown in Table 4. With the increase of flywheel inertia, the optimal start-up time corresponding to the optimal objective function value decreases, the impact degree and the utilization rate of inertial torque increase significantly, and the sliding friction work decreases in a small range. From the

Table 3: Optimization of different load values.

Load (%)	Start-up time T (s)	Sliding friction work (w)	Impact degree j (m/s^3)	Utilization rate of inertia torque	Value of objective function
100	4.204	108970	2.382	0.2754	0.6081
60	4.388	88848	1.512	0.2113	0.5217
30	4.571	72730	0.8433	0.1211	0.4562
0	4.755	54831	0.548	0.0818	0.4053

Table 4: Optimization results of rotational inertia for different flywheels.

Flywheel moment of inertia ($kg\cdot m^2$)	Start-up time T (s)	Sliding friction work (w)	Impact degree j (m/s^3)	Utilization rate of inertia torque	Value of objective function
0	4.38	113500	1.594	0.088	0.6192
30	4.29	113450	1.779	0.1797	0.6098
60	4.21	108960	2.558	0.311	0.5217
90	4.02	104450	3.956	0.5078	0.6434

objective function value, it can be seen that under full load, the optimal value of flywheel inertia is approximately 60. Therefore, in order to avoid affecting the soft start-up performance, the value of flywheel inertia should not be too large.

According to the comparative analysis, soft start-up performance and the optimal start time are different under different conditions. In the process of soft start-up of the scraper conveyor, due to the difference of loads and flywheel inertia, it is difficult to obtain the optimal performance of soft start-up with fixed start-up time. Therefore, it is necessary to study the influence of parameter variables on start-up time under multiple working conditions and get the two-parameter equation of optimal start-up time by a fitting method.

The optimal start-up time of multiple discrete working conditions can be obtained by experimental design and simulated annealing algorithm. The coal-laying length of the scraper conveyor and the input moment of inertia are taken as parameter variables, and the two-parameter calculation model of start-up time for the soft start-up process is obtained by the surface fitting method.

By fitting the output data, the response surface model of the soft start-up process start-up time with respect to two-parameter variables is constructed. By comparing the fitting surfaces of different orders, the reliability of the start-up time cubic fitting surfaces is the highest. The average error between the fitting equation and the sample points is 0.125%, and the fitting degree is 99%. The fitting results are shown in Figure 9. The fitting cubic regression equation is

$$\begin{aligned} T = {} & 4.718 - 0.00125 L_1 + 0.00153 J_0 + 8.62 \times 10^{-7} L_1^2 \\ & + 5.65 \times 10^{-7} J_0^2 - 1.45 \times 10^{-6} L_1 J_0 - 6.33 \times 10^{-10} L_1^3 \\ & + 1.8 \times 10^{-9} J_0^3. \end{aligned} \tag{18}$$

According to the fitting equation and surface, the optimal start-up time decreases with increasing load. The starting torque required for soft start of scraper conveyor under heavy load condition increases. Reducing the start-up time can effectively increase the inertial start-up torque and make full use of the input moment of inertia and the peak torque of the motor to start up. The optimum start-up time decreases monotonically with the decrease in the input moment of inertia. Under the same load, the larger input moment of inertia can store larger energy before the start-up. The increasing start-up time can reduce the influence of the soft start-up impact degree. In contrast, when the input moment of inertia is small, it is necessary to increase the starting angular acceleration to improve the inertial start-up torque. The optimization model can be applied to the soft start-up of scraper conveyor under different loads and flywheel inertia. Optimized start-up time of scraper conveyor can effectively utilize inertia torque, reduce sliding friction work and impact degree, and greatly improve the soft start-up for hydroviscous drive applied to the scraper conveyor.

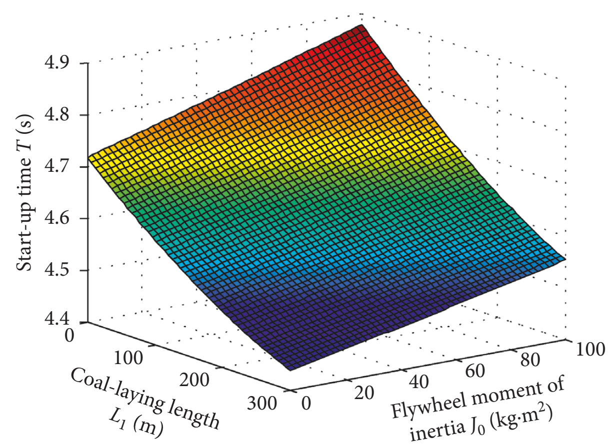

Figure 9: The fit optimal start-up time.

5. Conclusion

In order to improve the soft start-up performance and obtain the optimal soft start-up time of the scraper conveyor under different working conditions, the evaluation system for soft start-up performance is established based on the analytic hierarchy process. Through the joint simulation platform of MATLAB and Isight, the two-parameter control model for soft start-up time is established using the method of experimental design and simulated annealing algorithm. The optimal start-up time under different working conditions was determined, which provides a new method for optimizing the soft start-up performance of the scraper conveyor. The conclusions are as follows:

(1) When the soft start-up time of scraper conveyor is long, the output torque is stable, but the utilization rate of inertia start-up is low, and the sliding friction work increases. On the contrary, when the start-up time is short, the impact degree increases, the inertia utilization ratio is high, and the sliding loss power is small.

(2) The most significant factor affecting soft start-up performance of scraper conveyor is the start-up time. With the increase of start-up time, the objective function value of soft start-up performance decreases first and then increases. There is an optimal start-up time under different flywheel inertia and load values, which minimizes the value of the objective function with better soft start-up performance.

(3) Optimal start-up time can be determined by the response surface model for the soft start-up time, which takes into account the variables of load value and flywheel inertia. The optimal start-up time decreases with increasing load, and the optimal start-up time decreases monotonically with the input flywheel inertia.

(4) The optimized start-up time can greatly improve the soft start-up for hydroviscous drive. The optimization model established by joint simulation platform can be applied to the soft start-up of scraper conveyor under different loads and flywheel inertia.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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