Power Balance Control Strategy of Permanent Magnet Synchronous Motor of Belt Conveyor

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I. INTRODUCTION

In recent years, with the construction of intelligent coal mine and the continuous upgrading of the coal industry, the modern production and automatic control level of coal mining enterprises is getting higher and higher. As facing the new requirements of underground transportation in modern coal enterprises, especially in some high efficiency mines and special tunnel mines, the traditional single motor belt conveyor can no longer meet the requirements of modern production in terms of the performances and parameters. There is an urgent need for large-scale belt conveyors with high efficiency, long distance, and intelligent control [1].

Due to the longer conveying distance in the coal mine, the driving force of a single motor is not enough to drive the belt conveyor normally. If the power of a single motor is increased to enhance the driving force only, on one hand, the start of the high-power motor will have an impact on the power grid of the coal mine. On the other hand, the huge driving force will exceed the tension limit of the conveyor belt, and cause the belt to break, so the common large belt conveyors are often driven by multiple motors [2], [3], [4]. However, it is also accompanied complex system control problems by using multi-motor drive, the most prominent problem of which is the balanced load distribution among multiple motors. If the power distribution of motors is unbalanced, some motors will be overloaded and some motors will be under-loaded. The overloaded motor may stop, trip, or burn out due to excessive temperature, or even damage the entire belt conveyor system, causing impact and damage to coal mine production. Therefore, the research on the power balance of multi-motor belt conveyors has important theoretical and practical significance.
The power balance control methods of double-drum three-motor long-distance belt conveyor include master-slave control, parallel control, cross-coupling control, deviation coupling control, virtual spindle and other control methods [5], [6], [7]. Among the above-mentioned mainstream control methods for the double-drum and three-motor structure, the deviation coupling control method has a better control effect on two or more drive motors due to its unique closed-loop characteristics. The core of the method is the addition of a compensation mechanism, by calculating the speed deviation of each motor, summing the given speed of the control system, and then compensating it into the control loop of each motor. Although this method improves the synchronization accuracy among the motors, but it ignores the deviation between the motor speed synchronization error and the given error of the system, these problems such as complex compensation mechanism and poor performance will occur in the application.

II. ANALYSIS ON THE PRINCIPLE OF MULTI POINT COOPERATIVE CONTROL OF BELT CONVEYOR

Regarding the logic for speed control of the belt conveyor, the first step is to select the drive part which is the most sensitive to load changes as the main drive, and define one motor as the master drive motor, and other motors as the slave drive motors. The slave drive motors and the master drive motor adopt synchronous following control technology [8]. The master-slave drive system automatically calculates the speed according to the working conditions and the process and conducts real time interaction. When a drive fault or a power distribution fault occurs, it can coordinate and cooperate quickly, and can achieve a steady status within a specified time [9], [10], [11].

The dynamic analysis of belt conveyor was carried out by using Kelvin-Voigt model. The acceleration process of the belt conveyor makes it run according to the determined S-shaped curve, and the set acceleration V-t (speed-time) function formula can be written as

$$n_{gd2} = \begin{cases} at, & 0 \leq t < t_0 \\ A, & t_0 \leq t < t_1 \\ \frac{n_{gd1-A}}{t_2 - t_1} \times t, & t_1 \leq t < t_2 \\ n_{gd1}, & t \geq t_2 \end{cases}$$

(1)

The deceleration control curve of the belt conveyor is shown in (2) according to the set deceleration V-t function formula,

$$n_{gd2} = \begin{cases} n_{gd1}, & 0 \leq t < t_5 \\ \frac{n_{gd1-A}}{t_6 - t_5} \times t, & t_5 \leq t < t_6 \\ A, & t_6 \leq t < t_7 \\ -at, & t_7 \leq t < t_8 \end{cases}$$

(2)

In the above formula (1) (2), $n_{gd2}$ is the given speed from the host computer, $n_{gd1}$ is the given speed generated from the speed generator, $a$ is the acceleration determined by the acceleration and deceleration time of the inverter, $A$ is the entry speed determined by the inverter EMF model of the inverter characteristics, $t_0$ is the excitation time, $t_1$ is the belt conveyor tension transmission time, $t_2$ is the belt conveyor acceleration time, $t_3$ is the starting time of belt conveyor deceleration, $t_6$ is the end time of belt conveyor deceleration, $t_7$ is the starting time of the belt conveyor tension decrease, $t_8$ is the stopping time of the belt conveyor brake; in the above formula $a = At/50$, where $t = t_3, t_4, t_5, t_6$ are the acceleration and deceleration time of the inverter respectively.

In the drive motor control process, the torque output upper limit control $T-t$ (torque-time) under different given speed conditions is written as

$$T_{\text{max}} = \begin{cases} \frac{2}{3} T_{gd1}\gamma, & 0 \leq t < t_9 \\ 1.5T_{gd1}\gamma, & t \geq t_9 \end{cases}$$

(3)

Then the torque output lower limit control $T-t$ (torque-time) under different given speed conditions is shown and written as

$$T_{\text{min}} = \begin{cases} -\frac{2}{3} T_{gd1}\gamma, & 0 \leq t < t_{10} \\ -1.5T_{gd1}\gamma, & t \geq t_{10} \end{cases}$$

(4)

In the above formulas (3) and (4), $T_{\text{max}}$ and $T_{\text{min}}$ are the upper and the lower limit values of the output torque of the master drive and the slave respectively; $T_{gd1}$ is the rated output torque; $\gamma$ is the adjustable coefficient (experience data) of the output torque, and its function is to limit the output torque of the slave motor within a reasonable range of the demand of the driving host, so as not to oscillate; $t_9$ is the start time of drive force limit; $t_{10}$ is the end time of drive force limit.

III. DESIGN OF POWER BALANCE STRATEGY FOR MULTI MOTOR DRIVE

Taking the three-drive main coal belt conveyor system in most mines as the analysis background, when the belt conveyor is driven by multiple motors, the motors drive the rollers, and the rollers are connected by a belt. The friction between the rollers and the belt realizes the transmission of torque, and then drives the raw coal and other goods on the belt to run. Two of the three motors of the belt conveyor are coaxial and rigidly connected to drive roller A; another motor drives roller B. The rollers are connected by a belt, which is a flexible connection, as shown in Figure 1.

A. ANALYSIS OF CONTROL CHARACTERISTICS OF BELT CONVEYOR

1) COAXIAL RIGID CONNECTION

During rigid connection, the motors are constrained by rigid connection shafts, so the master-secondary control is suitable. Take one motor as the master, which adopts speed control, and the speed follows the given value; the other motor is the slave, which follows the given torque of the master to achieve balanced load distribution between two motors. The control block diagram is shown in Figure 2.
The control systems of the two motors share a torque regulator (ASR), which is placed in the master motor control system. Since the slave motor is connected to the master motor through a rigid shaft, the torque of the slave motor is the same as the master motor; the ASR outputs, given torque $T_e^*$ is used as the common torque of the master and slave motors, so that the actual running torque of the master and slave motors is equal to the given torque, to realize a balance load distribution.

In the control system shown in Figure 2, both ASR and ATL are PI regulators. If the rotation deviation angles at both ends of the rigid connection shaft are ignored, then the actual torque of the motor is approximately considered to follow the given torque without lag, and its motion equation as

$$\left(J_1+J_2\right)\frac{d\omega_m}{dt} + (B_1 + B_2) \omega_m = (T_e1 + T_e2) - T_L$$  \hspace{1cm} (5)$$

In the formula, $\omega_m$ is the rotation speed of the motor shaft, which is proportional to the rotation speed of the drum, $\omega_m = \frac{i_c}{i_c} \omega_{mg}$, and $\omega_{mg}$ is the rotation speed of the drum.

2) FLEXIBLE BELT CONNECTION

In the flexible connection, the synchronous operation of each motor speed cannot be guaranteed. Therefore, the master-slave theory of rigid connection cannot be used to achieve balanced power distribution. It is necessary to increase the speed to synchronize the speed of each motor. Using the characteristic that the characteristic curve of the motor can be shifted during frequency conversion control, the balanced distribution of load torque (power) on each motor can be achieved, so that the system can achieve power balance [12], [13], [14], and the adjustment of the flexible connection characteristic curve is shown in Figure 3.

When adjusting the motor characteristic curve, it is necessary to adjust the characteristic curves of the 1# and 2# motors at the same time. As shown in Figure 3, $a_1$ and $a_2$ are the adjustment coefficients of the 1# and 2# motors, so that the adjusted characteristic curves intersect at $T_L/2$, the balanced distribution of torque is achieved, the speed does not change, and the adjustment coefficient formula is obtained through below calculation.

$$\begin{align*}
a_1 &= 1 + \frac{k_1^2 - k_1k_2}{2\omega_0(k_1 + k_2)}T_L \\
a_2 &= 1 + \frac{k_2^2 - k_1k_2}{2\omega_0(k_1 + k_2)}T_L
\end{align*}$$  \hspace{1cm} (6)$$

Since the two rollers are connected by a belt, which is a flexible connection, in actual operation, due to the flexible characteristics of the belt, there are deviations in the rotational speed and torque. Since the two rollers are connected by a belt, which is a flexible connection, due to the flexible characteristics of the belt, there are deviations in the rotational speed and torque, so the control methods of the first two motors and the third motor are different. In the actual control system, the control method which the slaves follow the speed of the master can still be used. The master and the slaves both have speed regulators and torque regulators. The master and slave motors independently control the speed and torque. The master and slave speed regulators use the difference signal $K_b(T_1^* - T_2^*)$ of the master and slave torque regulators to fine-tune the speed in order to adjust the characteristic curve and achieve balanced load distribution. The control block diagram is shown in Figure 4.

In the figure, ASR and ATL are PI regulators, and Inv is a inverter. This control Strategy can suppress the longitudinal vibration of the belt, solve the slipping phenomenon within a certain range, and achieve load balance through the speed loop.
B. BALANCE CONTROL STRATEGY

1) TORQUE DISTRIBUTION: DEFINITION

The power distribution of the belt conveyor driven by 3 permanent magnet synchronous motors is as

$$P_i = \frac{P_{ei}}{\sum_{i=1}^{n} P_{ei}} P$$

In the formula: $P_i$ is the given power allocated by the permanent magnet motor; $P_{ei}$ is the rated power of the motor; $P$ is the load power, and satisfies $P = P_1 + P_2 + P_3$; $n$ is the number of motors, the value is 3, and The models and parameters which satisfies the motors are exactly the same. The belt conveyor system driven by three electric motors operates is as

$$P = P_1 + P_2 + P_3$$

$$P_1 = T_1 \omega_1$$
$$P_2 = T_2 \omega_2$$
$$P_3 = T_3 \omega_3$$
$$\omega_1 = \omega_2 = \omega_3$$

In the formula: $P_1$, $P_2$ and $P_3$ are the respective output powers of the three permanent magnet synchronous motors, the unit is KW; $T_1$, $T_2$ and $T_3$ are the electromagnetic torque of each motor, the unit is N m; $\omega_1$, $\omega_2$ and $\omega_3$ are the angular speed of the motor, the unit is rad/s. When the belt conveyor is running and the rotation speed of the three permanent magnet synchronous motors is guaranteed to be equal, the electromagnetic torque of the motor can be controlled to complete the balanced distribution of load power, which can be expressed as

$$T_i = \frac{T_{ei}}{\sum_{i=1}^{n} T_{ei}} T$$

In the formula: $T$ is the load torque of the belt conveyor, $T_{ei}$ is the rated electromagnetic torque of each permanent magnet synchronous motor, the unit is N m. According to the setting in Figure 1, No. 1 is the main motor, No. 2 and No. 3 are the slave motors, the torque distribution of the three motors can be expressed as

$$K = \frac{T_1}{T_2} = \frac{T_1}{T_3} = \frac{T_{ei}}{T_{ei}} = \frac{T_{ei}}{T_{ei}}$$

When the model and parameters of motor 1, motor 2 and motor 3 of the belt conveyor are the same, and the load distribution ratio of roller A and roller B is 2:1, $K = 1$.

2) POWER BALANCE CONTROL

Aiming at the double-drum and three-motor coal mine underground belt conveyor, the control system based on the deviation coupling structure is used to collect the rotational speed and current of three permanent magnet synchronous motors. After Clark and Park coordinate transformation, the d-q coordinate voltage equation is:

In the formula, $u_d$ and $u_q$ are the $d$ and $q$ axis components of the stator voltage vector; $i_d$ and $i_q$ are the $d$ and $q$ axis components of the stator current vector; $\omega_m$ is the electrical angular velocity; $\omega_m$ is the mechanical angular velocity; the electromagnetic torque is $T_e=1.5p\psi r_i q$, the load torque is $T_L$. The torque current value $i_q$ of the three motors is obtained, and the output power of the three motors is identified by $i_q$, so as to achieve the purpose of balanced distribution of the power of the three motors. The belt conveyor deviation coupling control system is shown in Figure 5.

Among them, taking the compensator of the first motor as an example, its structure is shown in Figure 6.

When the load of motor 1 changes or the disturbance is large, there will be a large deviation between the torque current value of motor 1 and the torque current value of motor 2 and motor 3. Based on the structure of the deviation coupling compensator in Figure 5, the torque current deviation value is compensated to the other two motors, and a coupling loop is formed between the three motors to achieve balanced load distribution of the three motors and improve the anti-interference ability of the system. That is, the torque current deviation is dispersed into the motor 2 and the motor 3, so that the operating states of the three-motor drive system remain consistent.

Then, the fuzzy ADRC controller is used for synchronous control, and the control structure is shown in Figure 7.
Among them, the ADRC controller consists of a tracking differentiator (TD), an extended state observer (ESO), and a nonlinear state error feedback control law (NLSEF). Among them, the function of TD is to extract the differential signal, give the error of the signal a reasonable transition process, and solve the conflict between the “rapidity” and “overshoot” of the control process. ESO classifies all disturbances as a state of the system, and converts the original system into a linear-integral series-type system through a dynamic compensation linearization process based solely on the input and output signals of the system. NLSEF greatly improves the control of the system by using nonlinear combination, which can speed up the convergence speed and suppress the steady-state error.

The fuzzy control unit includes three parts: fuzzification, fuzzy reasoning and clarity. In this process, the input precise quantity is converted into a fuzzy quantity by means of fuzzification, and then certain inference rules are used to perform fuzzy inference on the fuzzy quantity. Finally, the control quantity obtained by fuzzy inference is converted back to the precise quantity, so as to realize the control process of fuzzy ADRC. The above control process flow is shown in Figure 8:

By collecting and detecting the rotational speed and current of the three motors in real time, and using the compensator to compensate the torque and current deviation of the non-local motor to the local motor, and the motor speed is adjusted, so that the operating conditions of the three motors are consistent and synchronized, and the power balance control is achieved [15], [16], [17], [18], [19].

The multi-motor power balance process of the belt conveyor based on the deviation coupling structure is as follows: when the load of any permanent magnet synchronous motor changes, the torque current of motor 1, motor 2 and motor 3 will be biased. The output power of the three motors is unbalanced. The system compares the torque current of the other two motors with the torque current of this motor, and uses the compensator to compensate the current deviation value, and realizes the dynamic adjustment of the motor torque current based on the current deviation value. The torque currents of motor 1, motor 2 and motor 3 can form a coupling loop, and the torque current deviation and speed deviation can complement each other, so that the torque current can achieve dynamic balance. Finally, the load balance distribution of the power of motor 1, motor 2 and motor 3 is realized.

\[
\begin{align*}
v(t) &= \begin{cases} 
0, & 0 \leq t < 1 \\
\frac{2v_1}{t_1}(t-1)^2, & 1 \leq t < \frac{t_1}{2} + 1 \\
v_1 \left( - \frac{2(t-1)^2}{t_1} + 4(t-1) - 1 \right), & \frac{t_1}{2} + 1 \leq t_1 + 1 \\
v_1 \left( \pi - \cos \left( \frac{\pi}{t_1 + \tau + 1} \right) \right) + v_1, & t_1 + \tau + 1 \leq t < T + \tau + t_1 + 1 \\
v_e, & t \geq T + \tau + t_1 + 1
\end{cases}
\end{align*}
\]

(11)
In the formula, $t_1$ is the initial acceleration time, $\tau$ is the creeping time, and $T$ is the main acceleration time.

Set the startup process to 35s, the startup parameters to be $t_1 = 8s$, $\tau = 6s$, $T = 20s$, the startup speed curve and acceleration curve are shown in the figure 9:

It can be seen from Figure 9(a) that the belt conveyor has good starting performance, and the given belt speed is consistent with the actual belt speed; it can be seen from figure 9(b) that the acceleration of the main body of the conveyor at startup is less than 0.3 m/s$^2$. The only shock that exceeds 0.3 m/s$^2$ is the shock at about 15.8s, the maximum amplitude is 0.35m/s$^2$, and the shock recovery time is 120ms.

The speed tracking curve of each motor in the starting process of belt conveyor is shown in figure 10, where figure 10(a) is the tracking curve under PID control strategy, and figure 10(b) is the speed tracking curve under fuzzy ADRC control strategy.

It can be seen from figure 10(a), there is obvious overshoot phenomenon in the motor speed regulation process under PID control strategy, and the three motors have speed deviation in stable operation. In contrast, the speed tracking effect of fuzzy ADRC control strategy is good, and the response speed and overshoot phenomenon are better than PID control method. The starting process of conveyor under fuzzy ADRC control can meet the requirements of controllable starting of belt conveyor.

**B. SIMULATION EXPERIMENT OF SUDDEN LOADING**

At $t=40s$, a load torque of 270N·m within 0.02s is suddenly added, and the load torque jumps to 360N·m within 0.1s at...
t=45s. At this time, and the conveying speed of belt conveyor is shown in figure 11.

Obviously, the fuzzy ADRC control strategy can respond to the sudden change of load faster, and the adjustment time is shorter. The motor speed curve corresponding to the two methods is shown in figure 12, and figure 12(a) is the motor speed curve under PID control method, and figure 12(b) is the motor speed curve under fuzzy ADRC control strategy. Compared with PID control method, it can be found that the adjustment time of fuzzy ADRC control method is reduced by 0.44ms and 0.20ms respectively when dealing with two loads. Moreover, the PID control method gets larger speed deviation and worse speed tracking effect due to load change.

In the case of sudden load, the power distribution results of the two control methods are shown in figure 13, where the motor power variation with PID control strategy is shown in figure 13(a), and the fuzzy ADRC power distribution is shown in figure 13(b):

From the simulation results of PID control strategy, it can be seen that when the PID control strategy is adopted, when the load is sudden, the power deviation of each motor is large, the power deviation of motor 1 and motor 3 is 0.3kW, and the power balance effect of the flexible connected motor is poor. In contrast, in the fuzzy ADRC control method, the power of each motor changes rapidly, the speed response speed is less than 300ms, and the synchronization of the change is high. After the stability, the difference of the current of each motor is less than 0.1kW, and the output power of each motor is basically equal.

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