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Power Balance of Starting Process for Pipe Belt Conveyor Based on Master-Slave Control

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ABSTRACT An output power imbalance usually occurs in the driving motor of pipe belt conveyor due to the load disturbance and a variety of environmental interferences. This paper focuses on the operating condition of pipe belt conveyor where the head and tail with inclined angle are equipped with a motor separately. The discrete element method is used to propose a discrete model of the pipe belt conveyor, and its simulation model is established in the AMESim. According to the direct torque control method for the three-phase asynchronous motor, the principles for controlling the balance of dual-motor power are analyzed. A master-slave control strategy is proposed, where the master motor is controlled using a speed-given strategy and the slave motor is controlled using a torque-given strategy. A simulation model is built for the dual-motor driven system in the MATLAB-Simulink. After establishing a correlation between parameters through VS2010, a joint simulation model was established for the control system of the pipe belt conveyor. Simulation analysis and field test of the starting process are performed. Results of comparison with the traditional master-slave control strategy demonstrate the ability of the proposed method to balance the master-slave motor power of the pipe belt conveyor more effectively.

INDEX TERMS Mining equipment, master-slave, mathematical model, power control, pipe belt conveyor.

I. INTRODUCTION

The pipe belt conveyor is a novel closed-form conveying equipment, it can prevent the conveyed discrete materials (e.g., coal and ore) from leaking and dusting, thereby alleviating pollution to the environment. So it is increasingly used in the harbor, metallurgy and mining fields [1]–[5]. In recent years, many industrial applications expect longer conveying distances and greater productivity. The multi-motor, multi-pulley driven strategy is commonly adopted because the single-motor driven method is unable to meet the growing demand.

Being responsible for carrying and conveying the materials, the conveyor belt displays evident viscoelastic properties. Therefore, the pipe belt conveyor is prone to cause severe disturbance during the starting process, leading to imbalance of power allocated among the drive motor. In this context, a lot of attention has been paid to dynamic starting of pipe belt conveyor and power balance of multi-motor driven systems. An *et al.* [6] studied the propagation of elastic wave in the conveyor belt, and analyzed the starting of large-capacity long conveying distance belt conveyor, obtaining the law regarding low- and high-load starting. In this way, a controllable starting was implemented. Xi *et al.* [7] established a dynamic model for longitudinal vibration of the pipe belt conveyor using the finite element method, and a simulation model of the drive control system with feedback was built in the MATLAB-Simulink, then a starting process was simulated. Taking the partial differential equation and boundary condition of the carrying and returning sections into account, Song *et al.* [8] provided two different partial differential equations, and established the dynamic continuous model of the belt conveyor. The pattern of variation in physical quantities (e.g. displacement, speed and acceleration) at each point of the conveyor belt during the starting and stopping processes was determined. By studying dynamic starting of long-distance belt conveyor, Nuttall and Lodewijks [9] obtained the relation of dynamics of conveyor belt between the multi-motor driven belt conveyor and the single-motor driven belt conveyor. Li *et al.* [10] adopted the Kelvin model-based longitudinal dynamic equation to establish a viscoelastic model of the conveyor belt. The general coordinate method was used to determine the dynamic displacement and tension of the pipe conveyor. Halepoto and Khaskheli [11] established a dynamic model to describe the belt speed and load in the no-load, light-load and full-load cases, an efficient energy-saving conveyor was proposed. Yang [12] established a discrete element model of the belt conveyor based on the unique viscoelastic properties of the conveyor belt. Simulations were performed to analyze the variation in displacement, belt speed and tension of the conveyor belt during the starting process, it laying the theoretical foundation for the performance optimization of belt conveyor. Wang and Zhigang [13] discussed the power balance principles of the multi-motor driven belt conveyor, and proposed a Master-Slave control strategy where the master motor adopted speed control strategy and the slave motor adopted current control strategy. Wang *et al.* also proposed a master-slave control strategy for the multi-motor driven belt conveyor in [14], where the master motor exercises current-limited closed-loop control and the slave motor exercises the closed-loop power control. Han *et al.* [15] analyzed the common methods for power balance for multiple motor of the belt conveyor. By studying the application of differential fluid viscidity governor in the belt conveyor, Han proposed a method to balance power by exercising control over both speed and current, then correctness and feasibility of the proposed method were analyzed. Krasl and Ulrych [16] proposed a technology to optimize the power output response surface for the high-efficiency multi-motor driven system, the response surface method was adopted to model and optimize the power output of the multi-motor driven system. The above works have established the mechanical dynamics model for the belt conveyor, analyzed the properties of the system during the starting process through simulation, and discussed several approaches for power balance of the multi-motor driven system.

In this paper, the viscoelastic properties of the conveyor belt and the control method of the drive system are taken into account together, the factors involved in the imbalance of the dual-motor output power are analyzed. The relationship between the dynamics of the conveyor belt and the control performance of the driven system is fully considered. After studying the starting performance of the pipe belt conveyor in the actual operating condition, we propose a master-slave control method for dual-motor power balance of pipe belt conveyor, where the master motor is controlled using a speed-given strategy and the slave motor is controlled using a torque-given strategy. Research methods and technical lines are as follows:

Consider the operation condition where the head and tail with inclined angle are equipped with a motor separately. A discrete model was built using the discrete element method for the pipe belt conveyor. Its simulation model was then established in the AMESim. Based on direct torque control over the three-phase asynchronous motor, the principles for dual-motor power balance were analyzed, then a master-slave control strategy was proposed considering the viscoelastic properties of the conveyor belt. A simulation model was built for the dual-motor driven system in the MATLAB-Simulink, the parameter correlation between two software applications was implemented through VS2010, and then the simulation was performed upon the starting process of the conveyor. Power of the driving motor was tested under the full- and empty-load conditions. Analysis of test results demonstrates the control performance of the above dual-motor driven system.

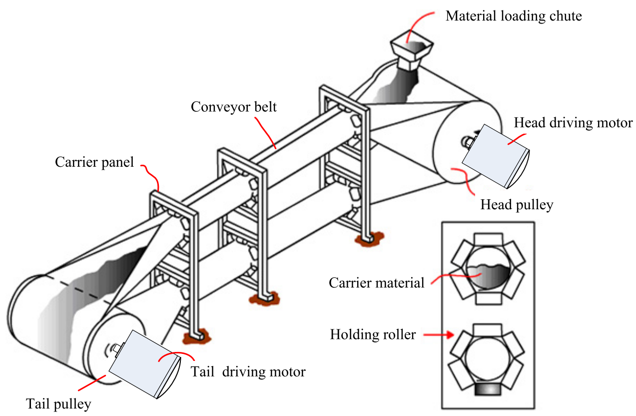


FIGURE 1. Parts of the pipe belt conveyor.

II. DISCRETE SIMULATION MODEL OF THE PIPE BELT CONVEYOR

The pipe belt conveyor mainly consists of Carrier panel, conveyor belt, pulleys, holding roller, driving system and tension device, as shown in Fig. 1. As one of the major components of bearing and conveying, the conveyor belt exhibits evident viscoelastic properties. The Kelvin equation [17] is used to build a discrete model of the conveyor belt, which is obtained by concatenating a mass block with parallel connection of linear spring and dampener.

Fundamental assumptions are necessary before modeling the mechanical parts of the pipe belt conveyor:

- the material is uniformly distributed on the load-bearing section.
- resistance of the load-bearing and return sections is uniformly distributed along the vertical direction of the conveyor belt. The simulated frictional resistance coefficient is linearly correlated with the belt speed.
- the equivalent quality of the rotation part of holding roller is uniformly distributed on the load-bearing and return sections along the vertical direction.
- the driving and tension devices are rigid.
- the conveyor belt twined around the pulley is rigid and its mass is negligible.

Based on above assumptions, the conveyor belt is divided into 16 discrete units in the AMESim, each of which is 12 m long and substituted with a Kelvin model capturing dynamics of the belt. In this way, a discrete simulation model of the pipe belt conveyor is built, as shown in Fig. 2. This model is head and tail dual-motor driven and hammer-tensed at the middle. The parameters of the pipe belt conveyor are given below:

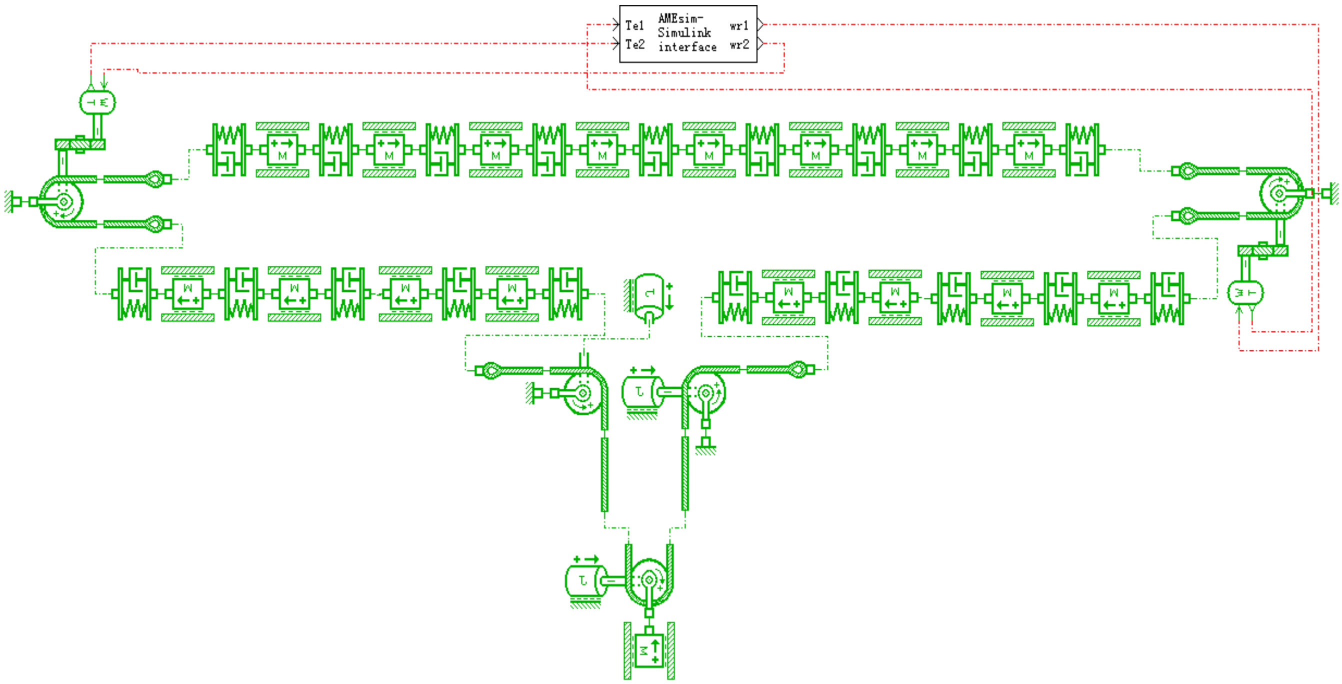


FIGURE 2. **Discrete simulation model of the pipe belt conveyor.**

Device length 96 m, unit conveyor belt length $l = 12$m, inclined angle $\theta = 20°$, single-hammer tensed, hammer weight $G = 800$kg, belt width $B = 1000$mm, pipe diameter $\phi = 250$mm, mass of unit conveyor belt $q_B = 16$kg/m, equivalent mass of holding roller in the load-bearing and return sections per unit length are $q_{RO} = 17.8$kg/m and $q_{RU} = 9.2$kg/m respectively, elastic modulus of the conveyor belt $E = 6787$kN/m, belt speed during stable operation $v = 1.85$m/s, conveying capacity $270t/h$, mass of the materials per meter $q_M = 44$kg/m, static coefficient of friction between material and belt $f_0 = 0.3$, resistance of cylinder forming $F_C = 318$N.

The parameters of the unit conveyor belt model can be computed as follows:

The mass of the unit of the load-bearing section is:

$$m_{RO} = (q_B + q_M + q_{RO})l = 933.6\text{kg}$$

The mass of the unit of the return section is:

$$m_{RU} = (q_B + q_{RU})l = 302.4\text{kg}$$

The major resistance of the non-transitional load-bearing section is:

$$w_{RO1} = lf_{RO}g[q_{RO} + (q_B + q_M)\cos\delta] = 277.6\text{N}$$

The major resistance of the transitional load-bearing section is:

$$w_{RO2} = lf_{RO}g[q_{RO} + (q_B + q_M)\cos\delta] + F_C = 595.6\text{N}$$

The major resistance of the return section is:

$$w_{RO3} = lf_{RU}g(q_{RO} + q_B\cos\delta) = 97.6\text{N}$$

The rigidity coefficient of the conveyor belt is:

$$k = EB/l = 565588\text{N / m}$$

If the viscoelasticity time constant $\tau = 0.8$ for the conveyor belt, the damping coefficient of the conveyor belt is:

$$c = \tau \times (EB/l) = 452471\text{N/ (m/s)}$$

III. POWER BALANCE ANALYSIS OF THE DUAL-MOTOR CONTROL SYSTEM

The direct torque control refers to the strategy where the mathematical model of three-phase asynchronous motor and the physical quantities of controllers are analyzed in the stator coordinate system. The magnetic flux linkage and torque of the stator are directly defined as the control variables. By eliminating the need for magnetic field orientation, vector transformation and current control, the direct torque control strategy further improves the dynamic response ability of the motor control system.

Under direct torque control, the electromagnetic torque equation of three-phase asynchronous motor is:

$$\begin{aligned} T_e &= p\frac{L_m}{L_s'L_r}\psi_r \times \psi_s = p\frac{L_m}{L_s'L_r}|\psi_r||\psi|_s\sin(\rho_s - \rho_r) \\ &= p\frac{L_m}{L_s'L_r}|\psi_r||\psi_s|\sin(\delta_{sr}) \end{aligned} \tag{1}$$

wherein p denotes the number of pole pairs in the motor, ψ_s denotes the magnetic flux linkage vector of the stator, ψ_r denotes the magnetic flux linkage vector of the rotator, i_r denotes the current vector of the rotator, L_s' denotes the transient inductance of the stator, L_m denotes the equivalent magnetizing inductance of stator and rotator, L_r denotes the equivalent self-inductance of rotator, ρ_s, ρ_r denote the electric angle of stator and rotator magnetic flux linkage vector with respect to the A-axis space, δ_{sr} denotes the load angle.

During actual operation of three-phase asynchronous motor, $|\psi_r|\,|\psi_s|$ can be regarded as constant. Therefore, the electromagnetic torque T_e can be controlled effectively by adjusting the load angle δ_{sr}.

The output torque and power of the pipe belt conveyor are compatible with this condition:

$$P = P_1 + P_2 = T_{e1}w_{r1} + T_{e2}w_{r2} = (T_{e1} + T_{e2})w_r \quad (2)$$

Wherein P_1, P_2 denote the output power of motor, T_{e1}, T_{e2} denote the electromagnetic torque of motor, w_{r1}, w_{r2} denote the angular velocity of motor, w_r denotes the synchronous angular velocity of motor.

From Equations (1) and (2), it can be seen that:

$$P = P_1 + P_2 = p\frac{L_m}{L_s' L_r}\,|\psi_r|\,|\psi_s|\,w_r\,[\sin(\delta_{sr2}) + \sin(\delta_{sr2})] \quad (3)$$

wherein i_{T1}, i_{T2} denote the current torque component of the stator.

From Equation (3), it can be learned that the power balance of the dual-motor driven system can be achieved by adjusting the two motor' load angles δ_{sr1}, δ_{sr2}. The load angle δ_{sr} is determined by the torque adjusting module of the motor driven system. The output of speed regulator T_e^*, i.e., the reference value of the electromagnetic torque, is the adjustable input signal to the torque adjusting module. Therefore, the load angle δ_{sr} can be controlled through T_e^*.

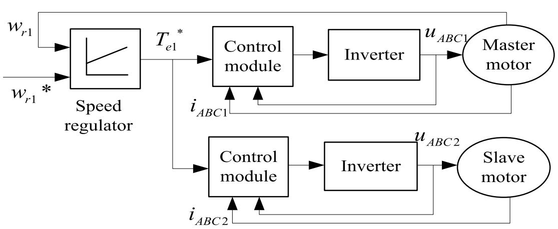


FIGURE 3. **Principles for power balance of the dual-motor driven system.**

Fig. 3 illustrates the principles for power balance of the dual-motor driven system. It can be observed that the master motor adopts the speed closed-loop control and the slave motor adopts the torque control. Moreover, the output T_e^* of the speed regulator of the slave motor is the input to the slave motor. This proposed master-slave control strategy of the dual-motor driven system adapts the torque input of the slave motor to the output of the master motor' speed regulator, thereby balancing the output power of the master and slave motor.

IV. JOINT SIMULATION AND EXPERIMENT

A. SIMULATION MODEL

According to the direct torque control principles and analysis above, a simulation model of the dual-motor driven control system of pipe belt conveyor is built in the MATLAB-Simulink, as shown in Fig. 4.

The model consists of the master-motor driven subsystem, slave-motor driven subsystem and the AMESim-Simulink communication interface module. The master-motor driven subsystem is responsible for rotational speed control, while the slave-motor driven subsystem is responsible for torque control based on the output of the speed regulator in the master-motor driven module. The parameters of the master and slave motor are: the rated power $P_n = 37$kW, rated voltage $U_n = 380$V, rated frequency $f_n = 50$Hz, stator resistance $R_s = 0.087\Omega$, rotator resistance $R_r = 0.228\Omega$, stator self-induction voltage $L_s = 0.8$mH, rotator self-induction $L_r = 0.8$mH, the number of pole pairs $P = 2$, stator-rotator mutual inductance $L_m = 74.13$mH, rotational inertia $J = 0.662$kg.m^2.

B. JOINT SIMULATION AND RESULT ANALYSIS

Interface communication between AMESim and MATLAB is implemented through Microsoft Visual C++ 2010 together with the S function. The AMESim interface module is generated in MATLAB-Simulink, and then connected with relevant input and output interfaces. After appropriately setting the rotational speed input signal and other necessary parameters, the system is started under the full-load condition, the simulation results are shown in Fig. 5 (a) and (b).

Fig. 5 (a) illustrates the curve describing the output torque of master and slave motor using the traditional master-slave control strategy. It can be seen that the ratio between the output torque of master and slave motor is about 1.05. This indicates that the output power of master and slave motor is not very balanced during the starting process of the pipe belt conveyor or especially in the case of abrupt change of the load. Fig. 5 (b) shows the output torque of master and slave motor using the proposed master-slave control strategy. It can be observed that the ratio between the output torque of master and slave motor approaches to 1. This indicates that the output power of master and slave motor is almost balanced when the pipe belt conveyor is started, stabilized or in the case of abrupt change of the load. And the proposed method is confirmed to be more effective in controlling the power, using a speed-given strategy for the master motor and a torque-given strategy for the slave motor.

Fig. 6(a) shows the load of master and slave motor when the driving system adopts the traditional master-slave control strategy. Considerable difference in the load of master and slave motor can be seen from the figure, and the ratio is approximately 1.06 during stable operation of the pipe belt conveyor. Fig. 6 (b) shows the load of master and slave motor when the driving system adopts the proposed master-slave control strategy, resulting in a ratio of almost 1. This demonstrates the ability of the proposed strategy to

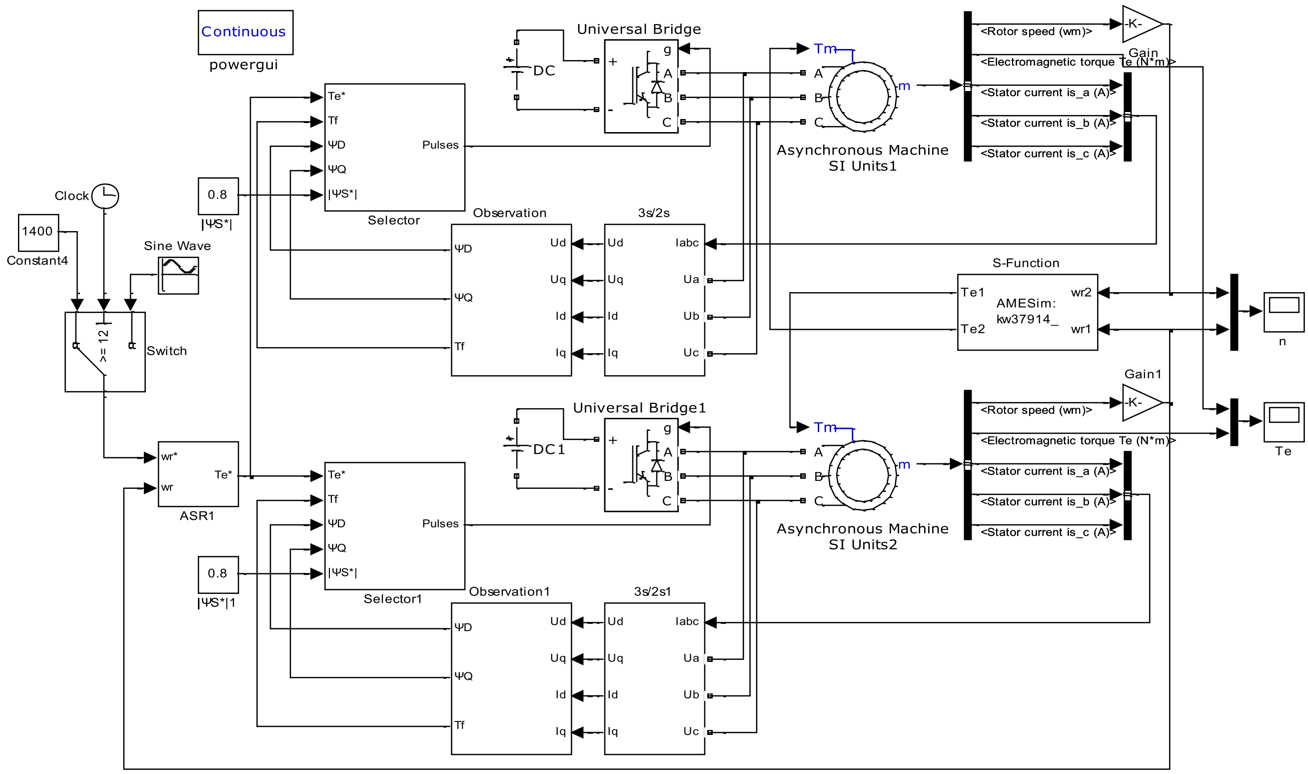


FIGURE 4. **Simulation model of the dual-motor driven system of pipe belt conveyor.**

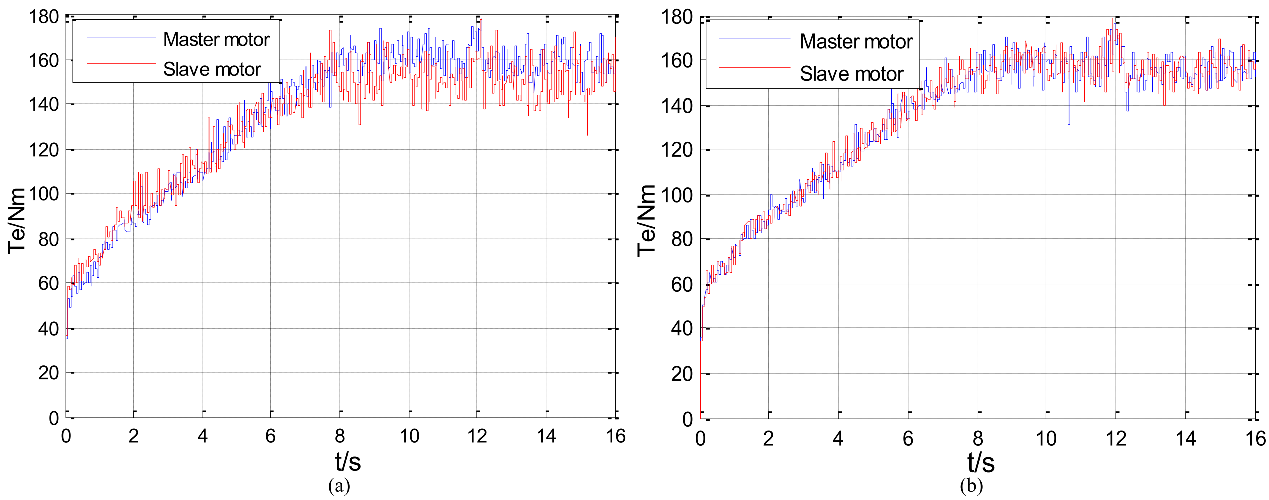


FIGURE 5. **(a) Output torque under the traditional master-slave control strategy. (b) Output torque under the proposed master-slave control strategy.**

balance load of the pipe belt conveyor. Analysis also indicates that the pulley load difference between the head and tail is a major contributor to output power imbalance of the drive motor. It can be learned from the Fig. 6 (a) and (b) that the abrupt change of pulley load at the tail in 11.5 s leads to an increase in the load on slave motor and a decrease in the load on master motor. After 12 s, the balance is nearly restored. During the time of 11 s -16 s, the sum of the load on the master and slave motor is constant. It means that after the system operates stably, the variation in the pulley load has no impact on the overall load of the pipe belt conveyor.

V. TESTING ON POWER BALANCE

Testing on output power was performed using the prototype of pipe belt conveyor jointly developed by TIDFORE Corp.

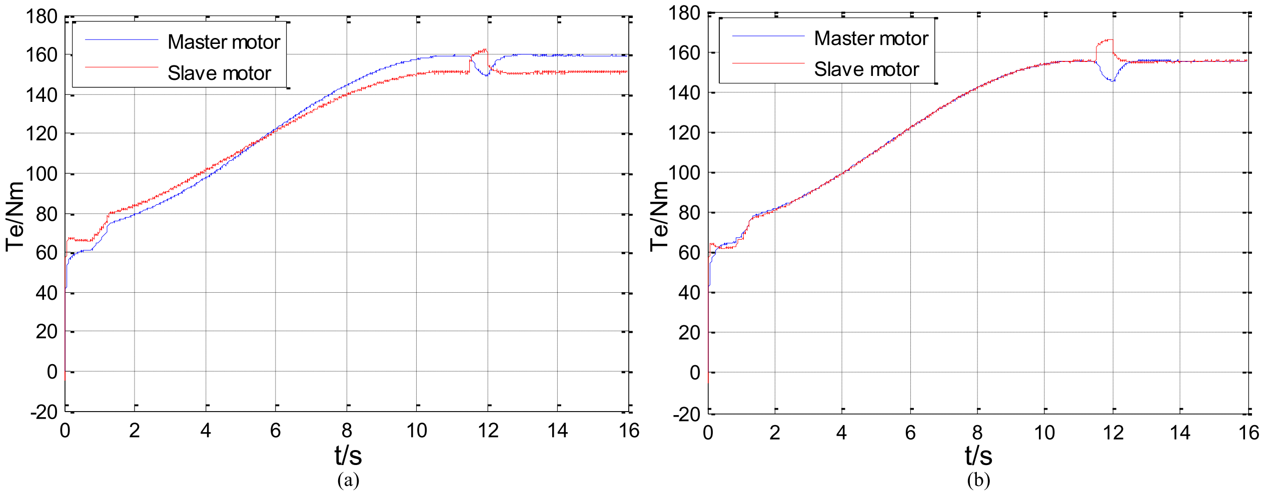


FIGURE 6. (a) Load achieved using the traditional master-slave control strategy. (b) Load achieved using the proposed master-slave control strategy.

FIGURE 7. Testing on power balance of pipe belt conveyor.

and our team, as shown in Fig. 7. The testing system consists of JYY-100 torque-speed and power tester, torque-speed sensor, and the control center.

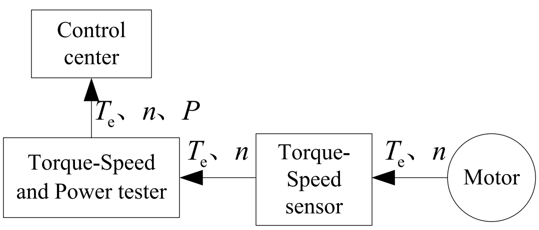


FIGURE 8. Principles of the drive motor power test system.

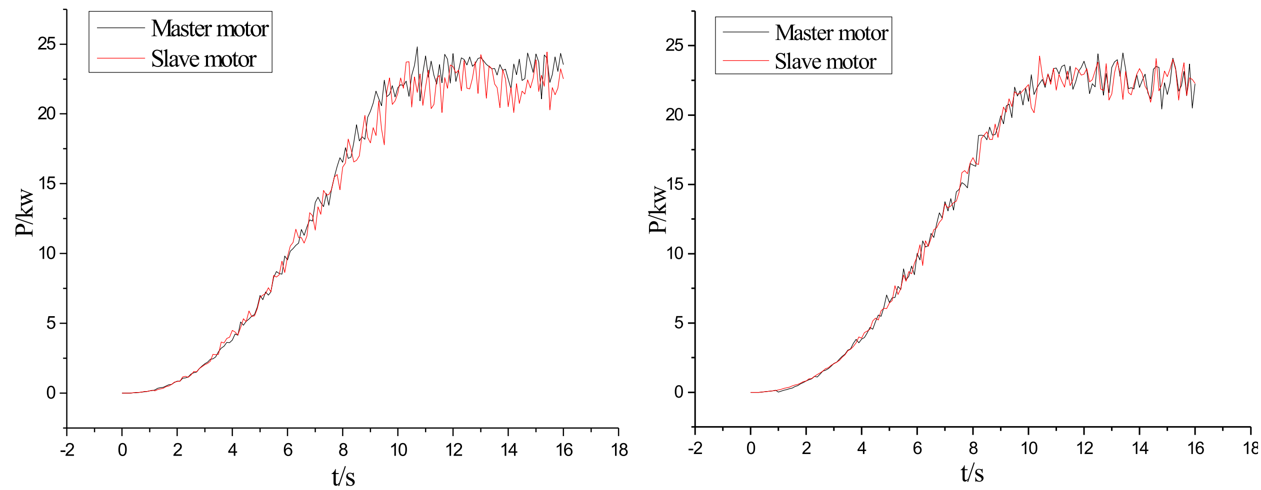
The operating principles of the test system are shown in Fig. 8. The torque-speed and power tester is able to output torque and speed using the motor detected by the torque-speed sensor, computing the output power of the drive motor. Meanwhile, the data collection module of the control center processes T_e, n, P from the torque, speed and power tester.

After confirming that all devices operate normally, the pipe belt conveyor is started under the full-load condition. The data sampling time of the test system is set to 0.1 s. In this way, the output power of master and slave motor is obtained under the full-load condition, using the traditional or proposed strategy with the same given speed of the conveyor belt, as in Fig. 9 (a) and (b). It can be observed that the output power of the motor increases with time after the pipe bet conveyor is started, until it operates stably. Using the proposed method, the output power of the motor ranges from 21-24 kW, instead of the range of 20-25 kW by the traditional strategy, the processing time from starting to stable running of 10.5 s, instead of 11 s by the traditional strategy. This shows that the proposed control strategy is able to control the output power of the motor of pipe belt conveyor more accurately and effectively.

TABLE 1. Sampled power of motor using the traditional strategy.

Time points (s)	Master motor power (Kw)	Slave motor power (Kw)	Absolute error (Kw)
2	0.869	0.834	0.035
4	3.803	4.684	0.881
6	9.549	10.290	0.741
8	16.943	16.180	0.763
10	21.884	21.192	0.692
12	24.326	23.382	0.944
14	22.496	20.524	1.972
16	23.527	22.520	1.007

Additionally, we extracted 8 sampling points for every 2 seconds from figures above for comparison. The results are shown in Tables 1 and 2. It can be observed that under the full-load condition, the absolute error range of the output power is 0.029-0.734 kW using the proposed strategy, instead of 0.035-1.972 kW using the traditional strategy. Therefore, the absolute error of output power of the motor is smaller using the proposed strategy, demonstrating the ability of the proposed strategy to balance power of master and slave motor of pipe belt conveyor more effectively and accurately.



(a) (b)

FIGURE 9. (a) Output power using the traditional master-slave control strategy. (b) Output power using the proposed master-slave control strategy.

TABLE 2. Sampled power of motor using the proposed strategy.

Time points (s)	Master motor power (Kw)	Slave motor power (Kw)	Absolute error (Kw)
2	0.814	0.843	0.029
4	3.831	3.908	0.077
6	10.214	9.920	0.294
8	16.311	16.923	0.612
10	21.000	21.699	0.699
12	23.667	22.933	0.734
14	22.982	23.550	0.568
16	22.266	22.784	0.518

VI. CONCLUSIONS

A discrete model of the pipe belt conveyor is established based on the discrete element of the conveyor belt. The three-phase asynchronous motor direct torque control method is adopted to analyze the dual-motor power balance principles. A master-slave control strategy is proposed, where the master motor is controlled using a speed-given strategy and the slave motor is controlled using a torque-given strategy. A simulation model is built for the dual-motor power balance system. Simulations and testing are performed to demonstrate the advanced performance of the dual-motor drive system of the pipe belt conveyor by proposed master-slave control strategy. We came to the following conclusions:

(1) The ratio of load between master and slave motor approaches to 1. Comparison with the traditional master-slave strategy shows that the difference of load between the pulleys at the head and tail is the major contributor to imbalance in the output power of dual-motor driven system.

(2) Abrupt changes occur to the pulley at the tail during the starting process, but the load of master and slave motor remains unchanged. Hence, it is inferred that the variation of load on the pulley has no impact on the overall load of the pipe belt conveyor.

(3) Simulation and testing on the power demonstrates the ability of the proposed strategy to balance power of master and slave motor in the pipe belt conveyor more effectively.

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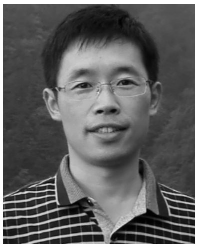

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