Simulation Method of Load Characteristics of High-power PMSM Drive System

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Abstract. This paper presents a simulation method of load characteristics of high-power permanent magnet synchronous motor (PMSM) drive system. According to the structural characteristics of the PMSM drive system of electric tractor, the load simulation experiment system is built to simulate the load characteristics of high-power PMSM. Next, on the basis of the similarity principle, the parametric equivalent scaling principle of the high-power PMSM drive system and experimental PMSM is established. Then, a dynamic load tracking algorithm is proposed based on the PI controller and the structure of load simulation experiment system, and the low-pass filter (LPF) is introduced to reduce noise interference caused by the differential term of speed. Finally, the numerical simulations and experiments are presented according to the schematic diagram of the load characteristic simulation and dynamic load tracking strategy. The results demonstrate that the proposed simulation method of load characteristics can effectively simulate the dynamic load of high-power PMSM drive system, which lays a foundation for the verification of the PMSM speed control strategy.

1. Introduction
Mining scraper conveyor is an important part of underground coal mining equipment, its PMSM drive system belongs to high-power electromechanical equipment, and the power of the PMSM is generally above 500kW. The operating conditions of the mining scraper conveyor are complex and variable, and its speed control stability requirements are relatively high. The simulation of the speed control strategy based on the electromechanical coupling model of the scraper conveyor and PMSM drive system cannot fully explain the effectiveness of the control strategy [1]. However, due to the lack of experimental conditions and funding, it is difficult to build a real high-power PMSM drive system in the laboratory to verify the effectiveness of the control strategy. Therefore, it is necessary to build a small-scale load simulation system under laboratory conditions based on the experimental method of system simulation [2]. Then, through the dynamic load simulation tracking method, the operating conditions embodying the load characteristics of the PMSM drive system of the mining scraper conveyor are simulated, which provide the research foundation of the speed control strategy of the high-power PMSM drive system.
Dynamic load simulation technology is a semi-physical experimental technique for simulating the force or moment load of a loaded object, and the load spectrum of the PMSM drive system is reproduced in the laboratory environment [3]. It provides a convenient and efficient means of discovering potential problems with the equipment or system, as well as studying various control algorithms [4]. Shang et al. used an electro-hydraulic torque load simulator to simulate the moment load of static friction and dynamic friction, and reproduced the real situation of the servo mechanism dragging large friction load [5]. Jing et al. proposed a friction electro-hydraulic loading scheme with load-testing by actuator or servo drive system, which solved the problem that the traditional load simulator was disturbed by the motion of the loaded object, and improved the accuracy of the load simulation in the laboratory environment [6]. A electric dynamometer was used as the load of the experimental motor in the literature [7]. Xu et al. developed a 200 kW fuel cell engine power system loading platform using a combined load structure with water resistance load and electric load [8]. Liu et al. designed the load simulation platform for the motor experiment used the magnetic powder brake as the load simulation component [9]. Muteba et al. built a PMSM dynamic test platform using the magnetic powder dynamometer, and carried out an experimental study on the dynamic characteristics of the novel synchronous reluctance motor with a sinusoidal anisotropic rotor [10].

In the research of dynamic load simulation loading strategy, Hewson et al. used the inverse model of the system to calculate the simulated torque, and realized the simulation of linear and nonlinear loads through the electric dynamometer [11]. Akpolat et al. pointed out that the system will become unstable when the moment of inertia of the load to be simulated is greater than twice the moment of inertia of the load simulation system [12]. Based on the forward dynamic equation of the system, Arellano-Padilla et al. calculate the dynamic response of the system to be simulated by measuring the torque of the system in real time [13]. Rodic et al. analyzed the frequency characteristics of the feedforward model tracking method, and pointed out that this algorithm needs to meet a certain frequency range in the application [14]. Guo et al. applied fuzzy neural networks to the simulation of dynamic loads [15], and Kyslan et al. introduced a simulation method for dynamic load simulation [16]. Based on the forward model tracking method, Ye et al. proposed a dynamic load simulation algorithm for electric dynamometer to simulate the load of automotive power system [17].

In order to comprehensively analyze the static and dynamic characteristics of the PMSM drive system of mining scraper conveyor and verify the effectiveness of its speed control strategy, this paper will build a small-scale load simulation experiment system based on the magnetic powder dynamometer. Based on this, the simulation method of load characteristics of PMSM drive system is proposed. The paper is organized as follows: The simulation principle of load characteristics is explained in the following section. The subsequent section presents the parametric equivalent scaling based on the similarity principle. Subsequently, the dynamic load simulation tracking method is established according to the PI controller and the structure of load simulation experiment system in the following section. The simulation and experiment results of proposed simulation method of load characteristics are provided next. The final section presents a brief summary of the study.

2. Simulation principle of load characteristics

![Figure 1. Structure diagram of PMSM drive system and load simulation experiment system: (a) PMSM drive system of the mining scraper conveyor; (b) load simulation experiment system.](image-url)
In the new PMSM drive system of mining scraper conveyor, the traditional “induction motor + reducer” transmission mode is replaced by a low-speed high-torque PMSM. Combined with the frequency converter, the soft start of the scraper conveyor is achieved. Therefore, the actual transmission system becomes a low-speed high-torque PMSM directly drives the scraper conveyor sprocket device through the coupling. The structure diagram of the PMSM drive system of mining scraper conveyor and the load simulation experiment system is shown in Figure 1.

In this paper, the dynamometer is used to simulate the dynamic response of the mining scraper conveyor system. The combination point of the dynamometer and the PMSM is the analog point [17]. The dynamometer loads the PMSM in the form of torque, and simulates the load through the control of the load torque. Finally, the structural diagram of the small-scale dynamic load simulation system is shown in Figure 2.

3. Parametric equivalent scaling

The PMSM in the experimental system and mining scraper conveyor are different in terms of rated power, rated speed, and moment of inertia. In order to enable the load simulation experiment system to accurately simulate the load characteristics of PMSM drive system, it is necessary to consider how to construct the parametric equivalent scaling according to the similar principle [18]. In this way, the equivalent load simulation is achieved by ignoring some of the factors that are not very important in the study.

Assuming that the parameters in the actual system and simulation system correspond one-to-one, and there are certain constant scaling factors in the process of system operation to convert the two systems, the two systems are called similar systems. Ignoring the influence of friction in the PMSM drive system, its kinematic equation can be written as:

\[ J_m^* \frac{d\omega_m^*}{dt} = T_e^* - T_L^* \]  

(1)

where \( J_m^* \) is the moment of inertia of the PMSM drive system, \( \omega_m^* \) is the rotational speed of the PMSM drive system, \( T_e^* \) is the electromagnetic torque of the PMSM drive system, and \( T_L^* \) is the load torque of the PMSM drive system.

Then, the kinematic equation of standard value system of PMSM drive system can be expressed as [19]:

\[ J_m \frac{d\omega_m}{dt} = T_e - T_L \]  

(2)

where \( J_m, \omega_m, T_e, T_L \) are the standard values of \( J_m^*, \omega_m^*, T_e^*, T_L^* \) (They are the parameters of the small-scale load simulation system). In the Eq. (2), \( t \) is not marked as \( t^* \) because the time similarity coefficient \( Z_t = 1 \). The similarity coefficients corresponding to the moment of inertia, angular velocity, electromagnetic torque and load torque are \( Z_I = J_m^* / J_m, Z_\omega = \omega_m^* / \omega_m, ZT_e = T_e^* / T_e, ZT_L = T_L^* / T_L \). After the PMSM is started, its output electromagnetic torque \( T_e \) is approximately equal to
the loaded load torque TL, and can assume $Z_{Te} \approx Z_{TL} = Z_T$. According to the above analysis, the Eq. (1) can be rewritten as:

$$Z_J \cdot J_m \frac{d\omega_m}{dt} = Z_T \cdot (T_e - Z_T \cdot TL) \approx Z_T \cdot (T_e - TL)$$

When the PMSM drive system of the mining scrapper conveyor and the small-scale load simulation system have similar characteristics, the similarity coefficient (ZT) of the loading torque can be obtained by combining Eqs. (2) and (3), and it can be expressed as $ZT = ZJ \cdot ZT$.

4. Dynamic load simulation tracking method

Considering the linear dynamics model of the PMSM drive system, you can get:

$$T_e - TL = J_m \frac{d\omega_m}{dt} + B_m \omega_m$$

According to the Figure 1(b), the mechanical equilibrium equation of the load simulation experimental system can be established as:

$$T_e - (J_m \frac{d\omega_m}{dt} + B_m \omega_m) = T_p + (J_c1 + J_c2 + J_p) \frac{d\omega_m}{dt} + B_p \omega_m$$

In order to achieve the purpose of load simulation, the following conditions must be met:

$$T_L = T_p + (J_c1 + J_c2 + J_p) \frac{d\omega_m}{dt} + B_p \omega_m$$

where $T_p$ is the output torque of the dynamometer, $J_c1$ is the moment of inertia of the coupling 1, $J_c2$ is the moment of inertia of the coupling 2, $J_p$ is the moment of inertia of the dynamometer, and $B_p$ is the coefficient of friction of the dynamometer. Therefore, it can be seen from the Eq. (6) that the load simulation of the PMSM drive system of the mining scrapper conveyor can be realized by controlling the output torque $T_p$ of the dynamometer in the small-scale load simulation system.

Considering the difference between the moment of inertia of the actual PMSM drive system and the small-scale load simulation system, the load torque control outer loop is added to the small-scale load simulation system. Subsequently, the load characteristics of the PMSM drive system are simulated by indirectly controlling the output torque of the dynamometer in the small-scale load simulation system.

In the small-scale load simulation system, the load torque $TL$ of the PMSM should be the sum of the torque $T_{Lm}$ measured by the torque sensor and the inertia torque of the coupling 1, as follows:

$$TL = T_{Lm} + J_{c1} \frac{d\omega_m}{dt}$$

Combined with the Eqs. (6) and (7), you can get:

$$T_{Lm} - J_{c2} \frac{d\omega_m}{dt} = T_p + J_p \frac{d\omega_m}{dt} + B_p \omega_m$$

Combined with the parametric equivalent scaling principle in section 3, you can get:

$$T_{Lm} = \frac{T_L}{Z_T} - (J_{c2} + J_p) \frac{d\omega_m}{dt} - B_p \omega_m$$
According to the Eq. (9), the load torque on the shaft of the small-scale load simulation system can be controlled to achieve the purpose of load simulation, and the dynamic compensation of the moment of inertia can also be achieved. Due to the differential term of speed in the above load simulation method (Eq. (9)), the differential is easy to cause noise interference error in the digital control system. Coupled with the lag caused by system sampling, the load simulation system is easy to cause oscillation, which affects the tracking control effect of dynamic load simulation. Therefore, a low-pass filter (LPF) is introduced in the small-scale load simulation system to reduce noise interference caused by the differential term of speed. Finally, according to Eqs. (5) and (9), the simulation principle of the small-scale load simulation system is shown in Figure 3 [20].

5. Simulations and experiments

5.1. Numerical simulations

In the author's previously published paper [1], the dynamic model of the mining scraper conveyor was established. Based on this, the numerical simulations of the load characteristic simulation method of PMSM drive system can be realized. The assumed dynamic load simulation conditions are as follows: First, let the mining scraper conveyor start at full load, and start working after 3s, this time is a random load; there is a sudden load change of 50% over the rated load at 5s, and lasts for 2s; after that, the mining scraper conveyor returns to normal random load state. The simulated load curve is shown in Figure 4.

According to the load curve and the electromechanical coupling model of mining scraper conveyor [1], the simulation results of the load characteristic of PMSM drive system can be obtained, and shown in Figure 5.
According to the relevant parameters of the small-scale load simulation system, the load simulation method of the PMSM drive system is simulated. In the small-scale load simulation system, the speed of PMSM is set to 150r/min. Based on the principle of parametric equivalent scaling, the similarity coefficient of the loading torque can be obtained as $Z_T = 137.93$. Combined with the schematic diagram of the small-scale dynamic load simulation system (Figure 2), the numerical simulations were performed under the same speed loop and current loop controller, and the results are shown in Figure 6.

Comparing the corresponding simulation curves of electromagnetic torque and load torque in Figure 5b and Figure 6b, it can be seen that the actual load characteristics of the PMSM drive system of mining scraper conveyor and small-scale load simulation system are similar. Meanwhile, the curves of speed (Figure 6a) and d-q axis currents (Figure 6c) of the PMSM in the small-scale load simulation system are in good agreement with the actual PMSM drive system (Figure 5a and Figure 5c). They reflect that the designed small-scale dynamic load simulation system and simulation method of load characteristics can realize the load characteristic simulation of the PMSM drive system of mining scraper conveyor. Moreover, the method proposed in this paper can be used to verify the effectiveness of the PMSM drive system speed control strategy, and can be used to comprehensively analyse and evaluate the static and dynamic characteristics of the PMSM drive system.

5.2. Load simulation experiments

According to the schematic diagram of the small-scale dynamic load simulation system of the PMSM drive system shown in the Figure 2, the experimental system is built and shown in Figure 7.
In order to further illustrate the effectiveness of the proposed load characteristic simulation method for PMSM drive system, the experimental verification was carried out on the experimental system. The experimental conditions are consistent with the numerical simulations, and the experimental results are shown in Figure 8. Comparing the load torque of the dynamometer in Figure 8b with the simulated load torque in Figure 6b, it can be seen that the trends of the two curves are consistent. From the comparison of the speed curves (Figure 8a and Figure 6a), it can be seen that the speed response of the PMSM is slower under the experimental conditions than the simulation, but their overshoot is relatively small. From the comparison of the d-q axis currents (Figure 8c and Figure 6c), it can be seen that the q-axis current output is relatively larger under the experimental conditions. The above shows that the simulation and experimental results have achieved good consistency, and the simulation method of the load characteristics of the PMSM drive system based on the parametric equivalent scaling principle is verified. In addition, the designed small-scale load simulation system and load simulation method can be used to verify the effectiveness of speed control strategy for the PMSM drive system.

6. Conclusions
Aiming at the problem that the load characteristics of high-power PMSM drive system are difficult to simulate, a dynamic load simulation tracking strategy is proposed based on the established small-scale load simulation system. According to the similarity principle, the principle of parametric equivalent scaling of PMSM drive system and small-scale load simulation system is established. Based on the inverse model principle, a dynamic load simulation tracking method is designed, and the low-pass filter is used to reduce the noise interference caused by the speed differential term. Subsequently, the compensation of the inertia difference between the small-scale load simulation system and the actual PMSM drive system of mining scraper conveyor is realized by adding a PI control outer loop to the load simulation system, and the numerical simulations and experiments are presented.

The simulation curves of the small-scale load simulation system have a good consistency with the curve trends of the actual PMSM drive system of mining scraper conveyor. It reflects that the dynamic load simulation method based on the parametric equivalent scaling principle is effective for simulating the load characteristics of the high-power PMSM drive system. The results of the load simulation
experiment based on the small-scale load simulation system are consistent with the corresponding numerical simulation results. It shows that the designed small-scale dynamic load simulation system and simulation method of load characteristics can realize the load characteristic simulation of the high-power PMSM drive system of mining scraper conveyor. In summary, the above results verify that the designed load characteristic simulation method and small-scale simulation system can be used to comprehensively analyze and evaluate the static and dynamic characteristics of the PMSM drive system of mining scraper conveyor. Moreover, the method proposed in this paper can be used to improve and perfect the control strategy of PMSM drive system.

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