A Research on Electric Inertia Simulation Technology Based on AC Induction Motor

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Abstract. In order to study the application of AC induction motor in electrical inertia simulation system, a simulation model of electrical inertia simulation system was established by MATLAB/Simulink. The closed-loop vector control strategy of the drive motor and load motor torque of the system is proposed after analyzing the theory of electrical inertia simulation. The angular acceleration of the system during acceleration and deceleration is obtained by approximation based on the system rotation speed measured. Thus, the automatic compensation of the inertia torque of the load motor is realized. A mechanical inertia disk was simulated. According to the results of the simulation, the speed error of the electric inertia simulation system is within 15 r/min, which indicates that this method can realize accurate inertia simulation.

1. Introduction

Compared to mechanical inertia, electric inertia simulation has many advantages, such as simple mechanical structure, convenient disassembly and adjustment, and stepless adjustment of inertia, so scholars at home and abroad have conducted extensive research on it\textsuperscript{[1-2]}. With the development of electrical inertia simulation technology, people have applied it to practical production, such as automotive inertial braking test bench, automotive transmission synchronizer test bench and wind power simulation system, etc. Taking the automobile brake test stand as the research object, the literature\textsuperscript{[3]} puts forward the control strategy of the electric inertia simulation system, and completes the simulation test and the result analysis with the simulation model. Combined with the characteristics of the inertial test bench of the automobile brake, the literature\textsuperscript{[4]} proposed three control methods including torque control method, speed control method and energy compensation method through the analysis of motor control methods. In both literatures\textsuperscript{[3-4]}, the DC motor was used as the drive system of the entire test stand to simulate the inertia of the car. DC motors have high production costs, difficult maintenance, and poor reliability although with the advantages of large starting torque, good speed control performance, and simple control. In recent years, high-performance AC motor control technology has developed rapidly, and AC motor systems are gradually replacing DC motor systems\textsuperscript{[5]}. It can be seen from this, the electrical inertia simulation technology is continuously improved though it has been implied in practice. With the development status of motor drive technology being considered, the slip frequency vector control principle is used in this paper to control the AC induction motor, which is used as both drive motor and load motor. By analyzing the basic principle of electrical
inertia simulation, we can draw the conclusion that the essence of electrical inertia simulation is real-time torque control of the load motor. Therefore, the PI regulator is used to perform torque closed-loop control of the drive motor and the load motor. In order to verify the correctness of the method in this paper, the models of mechanical inertia and electrical inertia simulation system were built by MATLAB/Simulink, and the curve of the torque and speed of the system during acceleration was obtained through simulation.

2. Theoretical Analysis

2.1 Electric Inertia Simulation Principle

Figure 1 is the structure sketch of electric inertia simulation system, of which the drive motor, torque/speed sensors and load motor are connected coaxially via the couplings, and both of the drive motor and load motor are AC induction motors. The drive motor is to provide the system with drive torque, and the load motor is to offer load torque and to simulate inertia torque. Besides, the torque/speed sensors are able to measure the torque and rotating speed of the system. In this thesis, in order to do the comparative experiment of the mechanical inertia and electrical inertia simulations, the mechanical inertia disk needs to be installed in the mechanical inertia test, and its installing position is shown in Figure 1.

![Figure 1. The Structure Sketch of Electric Inertia Simulation Test Bench.](image)

Electric inertia simulation means that the system can compensate for the inertia torque of the load motor without mechanical inertia, so that the system has the same speed change process, i.e. the same acceleration or deceleration, when it has the same drive torque as the mechanical inertia system.

When using this system for mechanical inertia experiments, according to Newton's second law of motion, the motion equation of the system can be obtained:

\[
T_d - T_l - T_f = (J_s + J_m) \frac{d\omega_s}{dt}
\]

(1)

In the equation (1): \(T_d\) is the drive torque; \(T_l\) is the load torque; \(T_f\) is the friction torque of the system; \(J_s\) is the inertia moment of the system; \(J_m\) is the mechanical inertia of the inertia disk; \(\omega_s\) is the angular velocity of the mechanical inertia system; and \(\frac{d\omega_s}{dt}\) is the angular acceleration of the mechanical inertia system.

When using this system for electrical inertia simulation experiments, the motion equation of the system can be obtained:

\[
T_d - T_l + T_i = J_s \frac{d\omega_e}{dt}
\]

(2)

In the equation (2): \(T_i\) is the inertial torque compensated for load motor; \(\omega_e\) is the angular velocity of the electrical inertia system; and \(\frac{d\omega_e}{dt}\) is the angular acceleration of the electrical inertia system.

According to the above analysis, the angular accelerations of the two systems are the same, i.e.:
\[
\frac{d\omega_m}{dt} = \frac{d\omega}{dt} = \frac{d\omega}{dt}
\]  

Therefore, combining the above three formulas, the inertia torque needed to be compensated by the load motor can be obtained:

\[
T_i = -J_m \frac{d\omega}{dt}
\]

(4)

It can be seen from the equation (4), when the system is accelerating, the system angular acceleration \((d\omega/dt) > 0\), so \(T_i < 0\). That is to say, the inertial torque compensated by the load motor is in the same direction as load torque. When the system is decelerating, the system angular acceleration \((d\omega/dt) < 0\), so \(T_i > 0\). Thus, the inertial torque compensated by the load motor is in the opposite direction as load torque.

Through the above analysis, in the electric inertia simulation experiment, the target torque applied to the drive motor is \(T_d\), and the target torque applied to the load motor is \((T_l - T_i)\). The directions of the two kinds of torque are opposite.

2.2 Slip Frequency Vector Control Principle

Using coordinate transformation, the three-phase AC stationary coordinate system \((u-v-w)\) is transformed into a two-axis rotating DC coordinate system \((d-q)\), and the electromagnetic torque of the induction motor can be expressed by formula (5):

\[
T_e = \frac{3}{2} p M L_r (i_{ds} \Psi_s - i_{qs} \Psi_q)
\]

(5)

In equation (5), \(T_e\) is the electromagnetic torque; \(p\) is the number of poles; \(M\) is the mutual inductance between the windings of each phase; \(L_r\) is the self-inductance of the rotor windings; \(i_{ds}\) and \(i_{qs}\) are the stator currents of the \(d\) and \(q\) axis separately; \(\Psi_s\) and \(\Psi_q\) are the rotor flux linkage of the \(d\) and \(q\) axis.

If the direction of the rotor flux vector is set as the \(d\) axis, then the rotor flux linkage in the \(q\) axis direction is equal to 0. Thus, the electromagnetic torque of the induction motor is proportional to the \(q\) axis stator current \(i_{qs}\). And we also know that the \(d\) axis rotor flux linkage is \(\Psi_{ds} = M i_{ds}\), so we can obtain electromagnetic torque:

\[
T_e = \frac{3}{2} p M^2 L_r i_{ds} i_{qs}
\]

(6)

It can be seen from the equation (6) that the electromagnetic torque of the induction motor can be controlled by controlling the magnitudes of stator currents of \(d\) and \(q\) axis.

3. Electric Inertia Simulation

3.1 Building the Simulation Model

The simulation model is built by MATLAB/Simulink. Because the electrical inertia simulation system is based on the closed-loop vector control of AC induction motor torque, the simulation model of the system mainly includes stator current closed-loop module, coordinate transformation module, field orientation module, SVPWM module and load motor target torque calculation module.

From section 2.2 we can see that the essence of the closed-loop control of induction motor torque is the closed-loop control of \(d\) and \(q\) axis’s stator currents. The \(d\) axis stator target current is fixed value of 0.6A. The \(q\) axis stator target current is calculated from the formula (6) based on the motor's target torque, and then it is closed-loop-adjusted by a PI regulator to maintain the motor's actual current fluctuations near the target current.
The target torque calculation module of the load motor is built based on the electrical inertia simulation principle. The angular velocity of the system can be obtained through the feedback of the motor. Therefore, when calculating the compensated inertia torque, the angular acceleration of the system can be obtained directly from the differential of the angular velocity. According to the section 2.1, the actual target torque of the load motor is \((T_l - T_i)\).

Integrate each module to get the simulation block diagram of electrical inertia simulation system, as is shown in Figure 2:

Figure 2. The Simulation Block Diagram of Electrical Inertia Simulation System.

3.2 Analysis of Simulation Results

The motor parameters of the electric inertia system simulation model are shown in Table 1:

| Parameters               | Value     |
|--------------------------|-----------|
| Rated Voltage /V         | 230       |
| Rated Power /W           | 184       |
| Rated Speed /(r/min)     | 1725      |
| Stator Inductance /H     | 0.316     |
| Mutual Inductance /H     | 0.294     |
| Number of Pole Pairs     | 2         |
| Moment of Inertia /(kg•m²)| 0.00098   |

Considering the moment of inertia of the torque sensor, drive shaft and coupling in the system, the moment of inertia of the entire electrical inertia simulation system is 0.0024 kg•m².

In the simulation, the voltage of the DC power supply is set to 80V, the drive torque of the drive motor is 0.4 N•m, and the load torque of the load motor is 0.3 N•m. The mechanical inertia is 0.00189 kg•m². The total time of the simulation model is set to 6s, the simulation step length is 10 μs, and the simulation results are shown in Figure 3 ~ Figure 6:
Figure 3. Comparison of Speed.

Figure 4. Comparison of Speed Error.

Figure 5. Comparison of Drive Torque.

Figure 6. Comparison of Load Torque.
As is shown in Figure 3 and Figure 4, under the effect of the acceleration torque, the motor speed rises evenly. Finally, as the drive torque is reduced and equal to the load torque, the motor speed is stabilized. Therefore, the electric inertia system designed in this paper can accurately simulate the change process of mechanical inertia system speed and the speed error is kept within 15 r/min, which shows the feasibility of the method in this paper.

As is shown in Figure 5, in the simulation, the drive torque of the drive motor rapidly increases from the beginning to the target value of 0.4 N·m and remains constant for a period of time. Then, due to the increase of the speed, the induced electromotive force increases, and the supply voltage of the DC power supply remains unchanged, making the drive torque of the drive motor cannot be stabilized at the target value for a long time and start to decrease. According to the simulation results of the simulation, it can be seen that the drive torque of the drive motor is maintained at the target value for a shorter time, and the time is about 3.5s. Finally, the drive torque is equal to the sum of the load torque and the friction torque of the system, thus, the system reaches equilibrium, and the drive torque is stable at around 0.34 N·m.

As is shown in Figure 6, since the inertia torque need to be compensated in the electric inertia simulation during the acceleration phase of the system, the load torque of the electric inertia is greater than the load torque of the mechanical inertia. When the system gradually reaches stability, that is, the rotational speed does not change substantially, the load torque of the electrical inertia gradually decreases, and finally the load torque is equal to the mechanical inertia of 0.3 N·m.

4. Conclusion
The simulation results show that if the electrical inertial simulations of the mechanical inertia is done by the method designed in this paper, the speed error is able to be controlled within 15 r/min. Therefore, in the electric inertia simulation system, based on the AC induction motor and using the method of this paper, the mechanical inertia system can be accurately simulated, thereby avoiding the inherent defects of the mechanical inertia system.

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