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Squirrel cage induction motor predictive direct torque control based on multi-step delay compensation

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ABSTRACT

The squirrel cage induction motor direct torque control main problems due to torque and large stator flux pulsation. In this an improved model predictive direct torque control algorithm considering multi-step delay compensation is proposed. At each sampling moment, predict the stator flux linkage and torque at the next moment under each voltage vector. The optimal voltage vector deviation from the stator flux linkage reference value and torque reference value are selected as the minimum objective function. Aiming at the problem of one-shot delay in digital control systems, a multi-step predictive delay compensation measure is studied. Simulation shows that the algorithm can effectively reduce torque and stator flux pulsation, reduce current harmonic distortion, and solve the delay problem in digital systems.

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1. INTRODUCTION

The direct torque control has a wide range of applications because of its good static and dynamic performance, but it has problems such as large output stator flux and torque ripple, and inconstant switching frequency [1]-[5]. Direct torque control (DTC) was proposed by M. Depenbrock [6] in the 1980s. In order to solve these problems, scholars have proposed many improvements. In particular, literature [7] and [8] proposed a new type of control technology-model predictive direct torque control (MPDTC) technology, which is simple in principle and easy to handle nonlinear constraints, but there are a lot of online calculations in the MPDTC control process, which may cause the delay problem of the control system [4]. However, in practical applications, the rotor inductance will change with the degree of magnetic saturation of the motor, and the rotor resistance will be affected by changes in the internal temperature of the motor [9]-[13]. The deviation of the rotor time constant will lead to wrong field orientation, which will deteriorate the system control performance [14], [15]. In response to this problem, many scholars have conducted in-depth research and proposed many online direct torque control identification schemes [16]-[19].

This paper introduces DTC model considering delay compensation. First, introduce the detail the induction motor model; secondly, derive the prediction model based on the analysis of the induction motor mathematical model, and predict the predicted value of the stator flux linkage and torque in 2 steps; thirdly, compare the predicted value of the stator flux linkage and torque with the absolute value of the deviation between the reference value of the stator flux and the torque is used as the objective function. Finally, the voltage vector control induction motor is selected to minimize the objective function value.

2. RELATED WORK

The flux linkage and torque of the induction motor in the two-phase stationary coordinate system can be expressed as (1)-(5) [20].

$$\frac{d\psi_s}{dt} = u_s - R_s i_s \tag{1}$$

$$\frac{d\psi_r}{dt} = R_r i_r + j\omega_r \psi_r \tag{2}$$

$$\psi_s = -R_s i_s + L_m i_r \tag{3}$$

$$\psi_r = L_m i_{rs} + L_r i_r \tag{4}$$

$$T_e = \frac{3}{2} pIM\{\psi_s \otimes i_s\} \tag{5}$$

Where: R_s 、R_r stator and rotor resistance; i_s 、i_r stator and rotor current vector; L_s 、L_r 、L_m stator self-inductance, rotor self-inductance and mutual inductance; ω_r rotor angular speed; p motor pole pair number.

3. PROPOSED MODEL

The MPC is an online optimization control algorithm based on discrete mathematical models. Its principle is simple and it has the advantages of easy introduction of nonlinear constraints [21]. The torque reference value T_e^* in the MPDTC control system is generated by the speed deviation of the proportional integral (PI) regulator, and the stator flux reference value ψ_e^* is set to the rated value, and the flux observation value is determined by the stator rotor The flux linkage observer calculates, and the torque and flux linkage predictor predicts the torque and flux linkage prediction value, and then establishes the objective function through the deviation between the predicted value and the reference value, and finally selects the voltage vector that minimizes the objective function To control the induction motor. The MPDTC control block diagram that this text puts forward is shown as in Figure 1. The voltage vector of the two-level voltage inverter is shown in Figure 2.

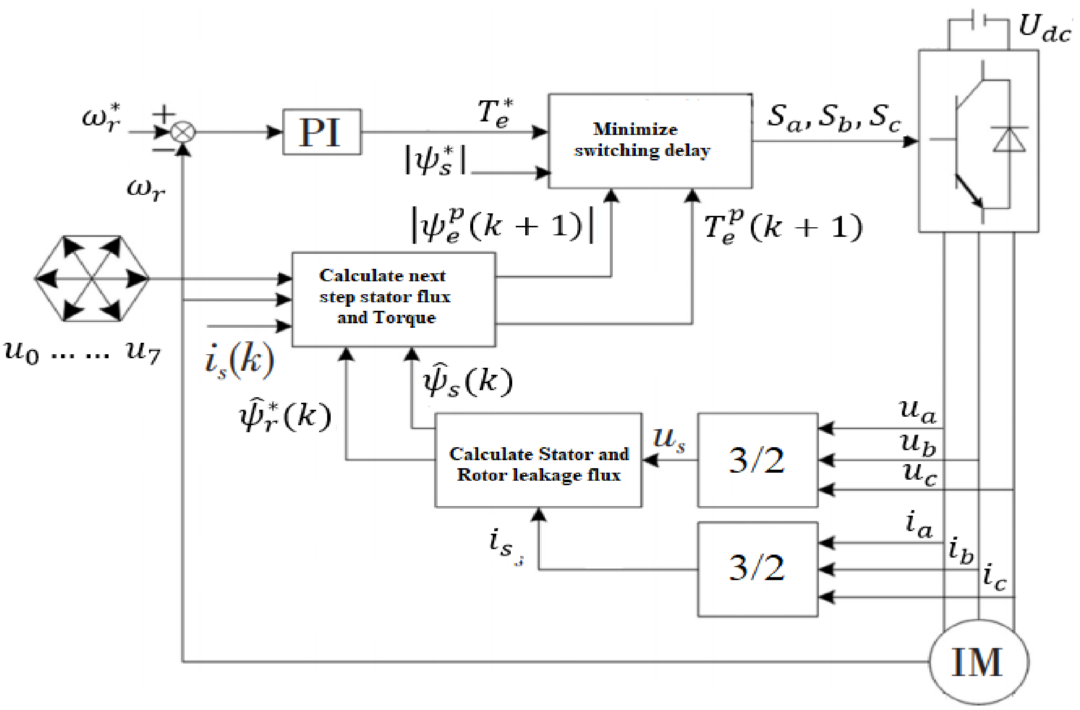


Figure 1. Proposed model prediction direct torque control

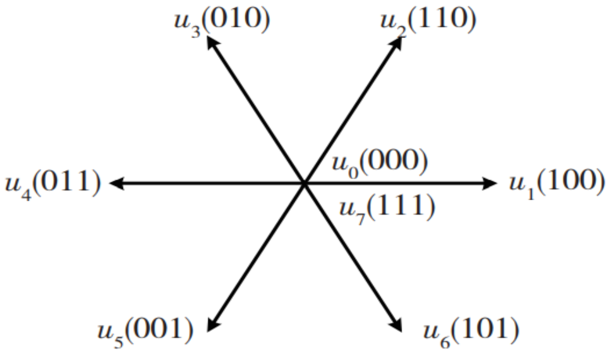


Figure 2. Voltage vector of two-level inverter

As a special case, if MPDTC selects a zero vector, u_0 or u_7 is selected based on the principle of switching the switch state only once. For example, the inverter output voltage vector was $u_1(100)$ at the last moment, then the zero-vector selected at the current moment should be $u_0(100)$, so that the switch state only needs to be switched once [22].

3.1. Flux link estimation

In this paper, the stator flux observer uses the U-I model [23], [24]. Current stator flux observation.

$$\hat{\psi}_s(k) = \int[u_s(k) - R_s i_s(k)]\mathrm{d}t \tag{6}$$

The rotor current is calculated by (3), and then the calculated rotor current equation is substituted into (4) to obtain the rotor flux equation.

$$\psi_r = \frac{L_r}{L_m}\psi_s + i_s\left(L_m - \frac{L_r L_s}{L_m}\right) \tag{7}$$

Obtain the observed rotor flux linkage as (8).

$$\hat{\psi}_r = \frac{L_r}{L_m}\hat{\psi}_s(k) + i_s(k)\left(L_m - \frac{L_r L_s}{L_m}\right) \tag{8}$$

3.2. Stator flux and torque prediction

The Euler's method can predict value of the flux linkage as (9).

$$\hat{\psi}_s^p(k) = \hat{\psi}_s(k) + T_s u_s(k) - R_s T_s i_s(k) \tag{9}$$

The induction motor stator current $i_s^p(\mathrm{k}+1)$is obtained from the stator dynamic equation as (10).

$$T_\sigma \frac{di_s}{dt} + i_s = \frac{k_r}{R_\sigma}\left(\frac{1}{T_r} - j\omega\right)\psi_r + \frac{1}{R_\sigma}u_s \tag{10}$$

Where: $T_\sigma = L_\sigma / R_\sigma$ stator discrete time constant; $L_\sigma = \sigma L_s$ motor leakage inductance; $\sigma = 1 - L_m^2/L_s L_r$ leakage inductance coefficient; $R_\sigma = R_s + k_r^2 R_r$ equivalent resistance; $k_r = L_m/L_r$ rotor coupling factor; $T_r = \frac{L_r}{R_r}$rotor electromagnetic time constant.
Use Euler's method to expand (10) to obtain the predicted value of stator current at k+1

$$i_s^p(k+1) = \left(\frac{T_\sigma + T_s}{T_\sigma}\right) i_s(k) + \frac{T_\sigma}{T_\sigma + T_s}\left\{\frac{1}{R}\left[\left(\frac{k_r}{T_r} - i_s j\omega\right)\hat{\psi}_r(k) + u_s(k)\right]\right\} \tag{11}$$

Substituting flux $\psi_s^p(\mathrm{k}+1)$ and stator current $i_s^p(\mathrm{k}+1)$ into (5), the predicted value of torque at k+1 can be obtained

$$T_s^p(k+1) = \frac{3}{2}pIm\left[\psi_s^p(k+1)\otimes i_s^p(k+1)\right] \tag{12}$$

The torque can quickly track the reference value while keeping the stator flux amplitude constant, so the objective function is constructed [9]

$$g = \left|T_e^* - T_e^p(k+1)\right| + \lambda \left||\psi_s^*| - \left|\psi_e^p(k+1)\right|\right| \tag{13}$$

Where the weight coefficient of the λ flux linkage amplitude.

3.3. Multi-step delay compensation

It can be seen from (9) and (11) that the predicted values of flux linkage and current are predicted by the current $i_s(k)$ and voltage $u_s(k)$ measured at the current moment and the observed flux linkage $\hat{\psi}_s(k)$ Yes, but due to the one-beat delay in the digital control system [9], [10], the selected voltage vector will not be updated until the next moment. Therefore, the current stator current and stator flux linkage have become$i_s(k+1)$ and $\hat{\psi}_s(k+1)$ respectively. Therefore, the variable at time $k+1$ is used as the initial value, and the variable at time $k+2$ is predicted to eliminate the influence of one step delay. The specific compensation measures are first to predict $i_s(k+1)$ and $\hat{\psi}_s(k+1)$ according to (9) and (11), and then based on $i_s(k+1)$ and $\hat{\psi}_s(k+1)$ And 7 kinds of voltage vectors $u_i(k+1)$ to predict the state variables at $k+2$ time. Finally, torque compensation based on the amplitude of the stator flux linkage at $k+2$, can be (14).

$$g = |T_e^* - T_e^p(k+2)| + \lambda ||\psi_s^*| - |\psi_s^p(k+2)|| \tag{14}$$

4. RESULT AND DISCUSSION

In order to verify the effectiveness of the above-mentioned predictive control algorithm, this paper builds an MPDTC system simulation model in MATLAB/Simulink [2]. The motor parameters of this model are shown in Table 1. The sampling period of the simulation system is $Ts = 50\ \mu s$.

Table 1. Simulation parameters

Parameter	Value	Parameter	Value
Power (kW)	2.2	Rr (Ω)	1.876
Supply (V)	380	Lm (mH)	223
F (Hz)	50	Ls (mH)	232
p	2	Lr (mH)	232
Rs (Ω)	3.125	Tn (N.m)	14
		Ψs (Wb)	0.92

Under the MPDTC control method considering delay compensation, the no-load start-up of the motor runs to 15 rad/s, the speed is increased to 75 rad/s in 0.3 s, and then the speed is increased to 150 rad/s in 0.5 s. The simulation results of the motor are shown in Figure 3. From Figure 3, it can be seen that the motor runs well at low, medium and high speeds and can quickly track a given speed. After entering the steady state, the stator current waveform is smooth and the torque ripple is small.

Figures 4-6 shows the simulation results for the three control methods of DTC, MPDTC with and without proposed delay compensation, start the motor with no load and run to 150 rad/s, apply load at 0.3 s, and then reverse to -150 rad/s at 0.5 s. Table 2 summarizes the speed drop value of the motor in Figures 4-6 after the rated load is suddenly applied to the motor in 0.3s and the torque ripple value after stable operation of the motor.

Table 2. Results comparison

Control Method	Speed drop (rad/s)	Torque ripple value (N·m)
Conventional DTC	8.77	8.5
Proposed MPDTC	8.95	2.5

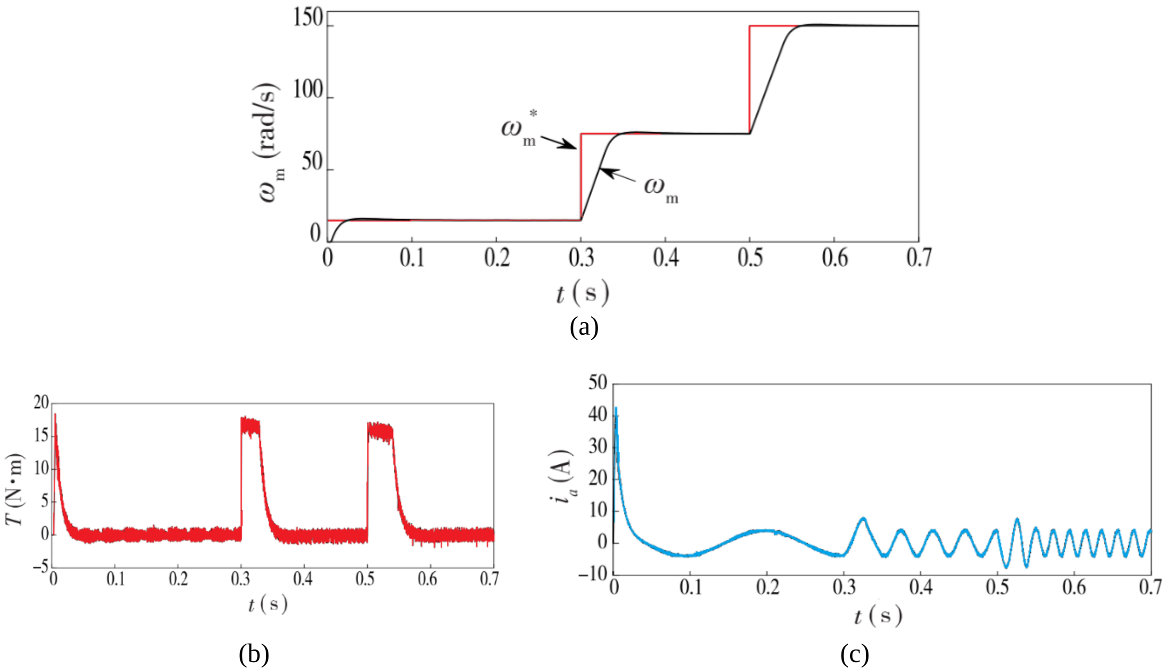


Figure 3. Simulation results of speed change; (a) Speed waveform, (b) Torque waveform, (c) Phase A current waveform

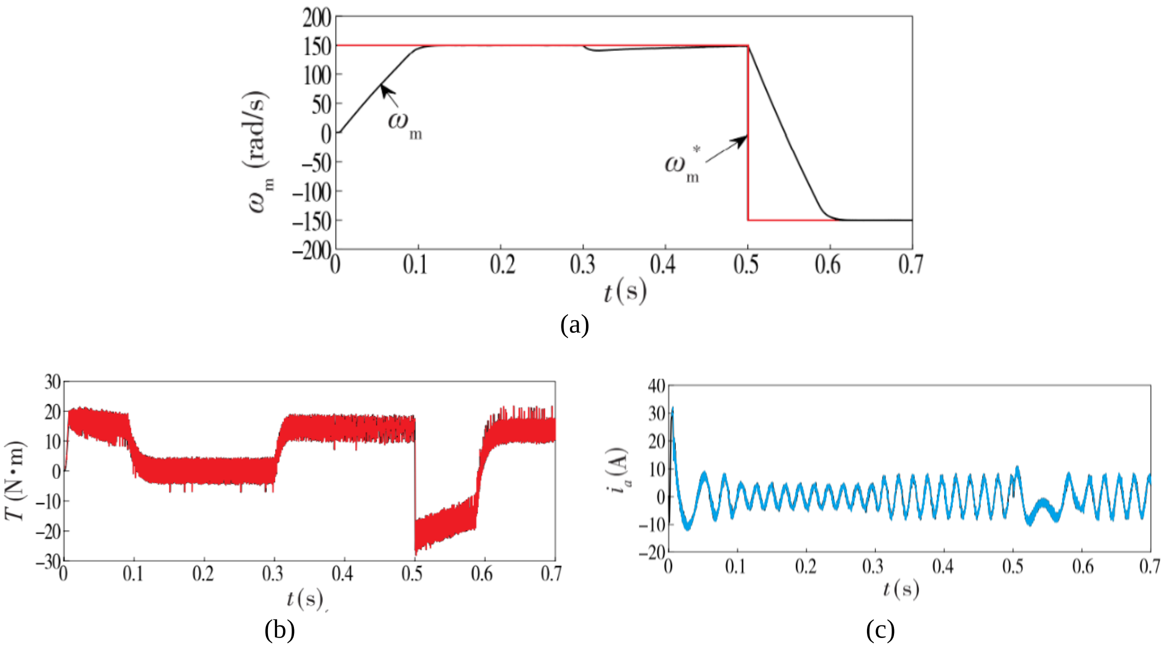


Figure 4. The simulation results of direct torque control: (a) Speed waveform, (b) Torque waveform, (c) Phase A current waveform

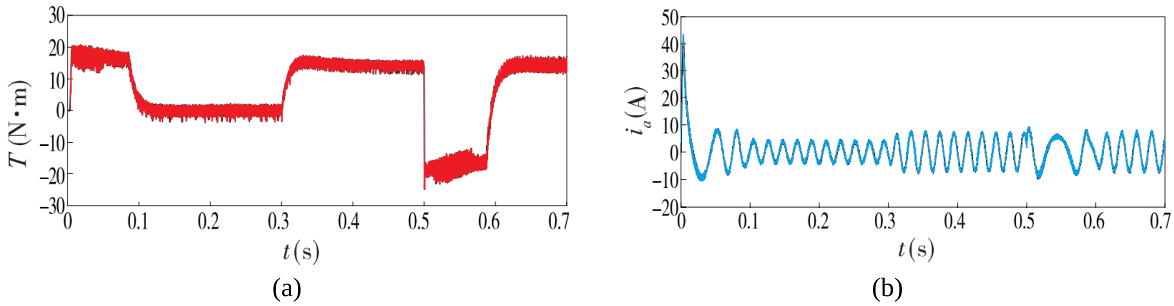


Figure 5. The simulation result of direct torque control with model prediction without delay compensation: (a) Torque waveform, (b) Phase A current waveform

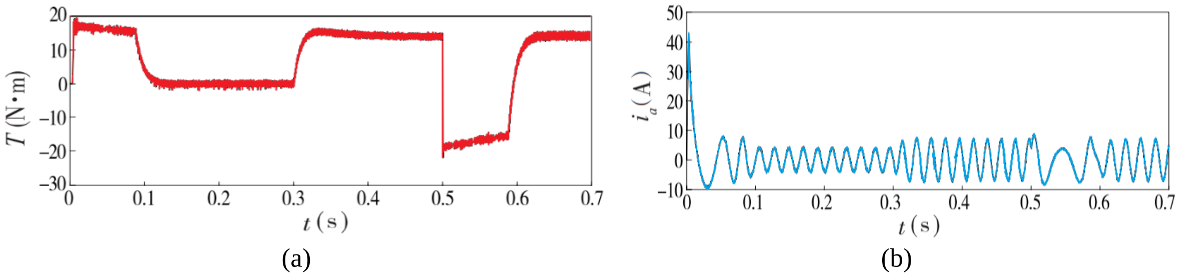


Figure 6. The model result with delay compensation to predict the DTC: (a) Speed waveform, (b) Torque waveform, (c) Phase A current waveform

From Figures 4-6 and Table 2, it can be seen that after the rated load is suddenly applied, the motor speed drop values of these three control methods are not much different, and they all quickly return to the steady state. The torque ripple value of the induction motor is the largest when the DTC method is used, and the torque ripple value is the smallest when the MPDTC method with delay compensation is used. It is proved that MPDTC with delay compensation has the best steady-state and dynamic performance. Under the three control methods of DTC, MPDTC without delay compensation and MPDTC with delay compensation, the current harmonic spectrum of the motor with rated load and stable operation at 40 Hz is shown in Figure 7. From Figure 7, it can be seen that the stator a-phase current THD of these three control methods are 17.53%, 9.93% and 5.28%, respectively. By comparison, it is found that the a-phase current THD of the MPDTC with delay compensation is the smallest, and the a-phase current waveform has no large glitches, and the waveform is relatively smooth. Figure 8 shows the two control methods of DTC, MPDTC without delay compensation and MPDTC with delay compensation, the stator flux trajectory of the motor. From Figure 8, it can be seen that the DTC flux trajectory circle has larger pulsation, especially when the sector is switched, the pulsation is greater, and the MPDTC flux trajectory studied in this paper has no obvious glitches and the pulsation is small, especially in the MPDTC method with delay compensation, the pulsation of the flux trajectory is smaller, which proves the effectiveness of considering delay compensation.

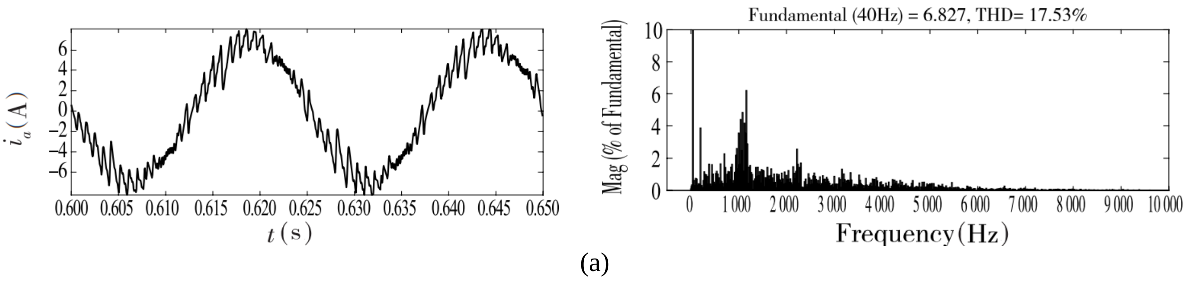
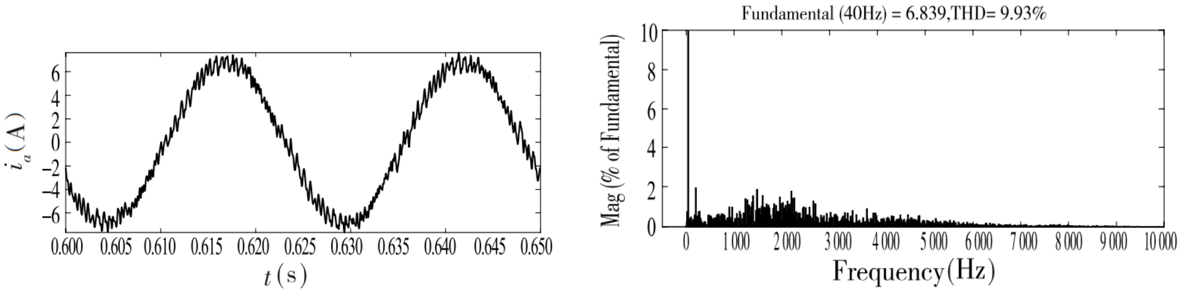
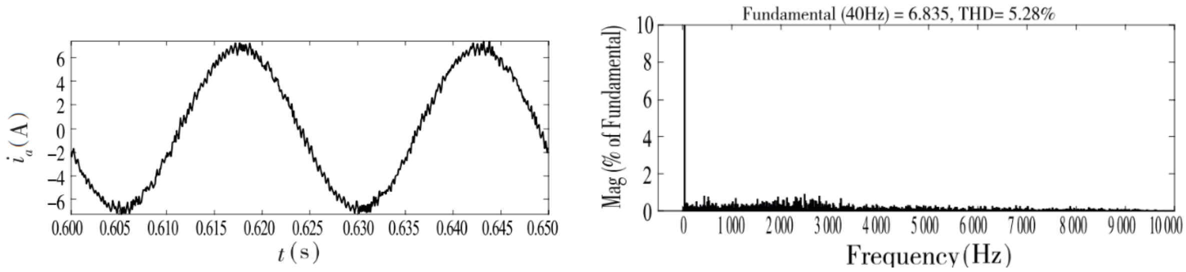


Figure 7. Induction motor phase current harmonic spectrum: (a) DTC

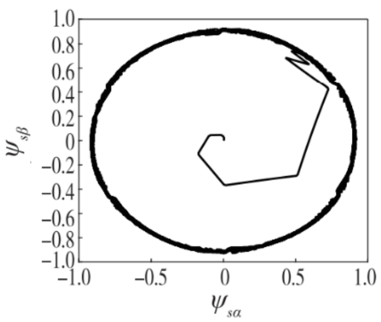


(b)

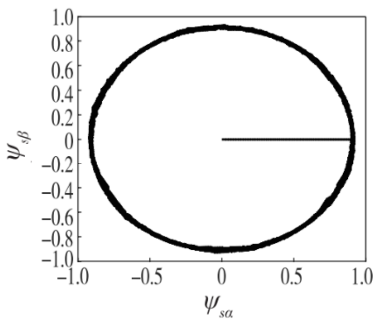


(c)

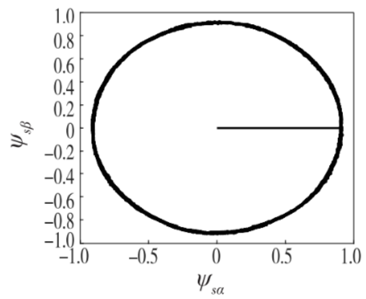
Figure 7. Induction motor phase current harmonic spectrum: (b) DTC without proposed model, (c) DTC with proposed model *(continued)*



(a)



(b)



(c)

Figure 8. Stator flux trajectory circle: (a) Direct torque control, (b) DTC without proposed model, (c) DTC with proposed model

5. CONCLUSION

This paper study a squirrel cage induction motor model predictive direct torque control method, builds an induction motor model for simulation, and studies a multi-step predictive delay compensation method for the one-shot delay problem in the digital control system. The MPDTC method can greatly reduce torque and flux pulsation, and reduce current harmonics. The simulation results show that the model predicts that the direct torque control induction motor system has good static and dynamic control performance during the operation process, and has good practicability

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