International Core Journal of Engineering
ISSN: 2414-1895

Volume 12 Issue 4, 2026
DOI: 10.6919/ICJE.202604_12(4).0020

Simulation Research on Direct Torque Control of Asynchronous Motors based on MATLAB

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Abstract

The direct torque control (DTC) technology of asynchronous motors, with its excellent dynamic response performance and simple control structure, has become the core research direction in the field of high-performance AC speed regulation. This paper deeply explores the basic theory of direct torque control, establishes the mathematical model of asynchronous motors in the stator coordinate system, and builds a complete simulation system using the MATLAB/Simulink environment. By introducing the flux observer, torque hysteresis comparator, and optimal switching table, the decoupling control of motor torque and flux is achieved. Experimental results show that this system exhibits strong robustness when subjected to sudden load changes and drastic variations in speed, effectively overcoming the complex coordinate transformation and strong parameter dependence problems in traditional vector control. The research in this paper provides theoretical references and simulation basis for optimizing the torque pulsation problem of the DTC system.

Keywords

MATLAB; Asynchronous Motor; Simulation; Mathematical Model.

1. Introduction

During the development of industrial automation and intelligent manufacturing, the AC motor is the main executive component of the power drive system. Its control accuracy and response speed determine the operational quality of industrial equipment. In the past period, asynchronous motors were more difficult to control than DC motors due to their nonlinear, highly coupled, and multi-variable physical characteristics[1]. In the 1980s, after the vector control FOC, the direct torque control DTC theory was proposed, which changed the fixed view of DTC as an analog decoupling control of DC motors. DTC did not use complex rotational coordinate transformations and current control loops, but directly controlled the stator flux and electromagnetic torque in the stator coordinate system through the state of space voltage vector switches[2]. With the continuous development of power electronics technology, high-speed digital signal processors DSP and MATLAB simulation tools are also widely used. This has made the application value of DTC technology in rail transportation, CNC machines, and new energy vehicle drive systems very obvious.

2. Mathematical Model of Asynchronous Motor and Analysis of Direct Torque Control Mechanism

2.1 Mathematical Modeling of Asynchronous Motor in Static Stator Coordinate System

To achieve direct torque control, it is necessary to first establish the mathematical model of the asynchronous motor in the stator static coordinate system (α-β coordinate system). According to the electromagnetic induction law and Kirchhoff's law, the voltage equation of the motor can be expressed as the relationship between the stator voltage and current, magnetic flux, and the rate of change of magnetic flux, that is, us = Rs is + dψs/dt. In the stator coordinate system, the magnetic flux equation and current equation are coupled through the inductance matrix, where the relationship between the stator magnetic flux ψs and the rotor magnetic flux ψr determines the mechanism of electromagnetic torque generation[3]. This paper details the derivation of the magnetic flux trajectory equation, indicating that in the case of ignoring the resistance drop of the stator, the change in the stator magnetic flux is proportional to the action time of the stator voltage vector. Through the state space description of physical quantities such as motor speed, current, and magnetic flux, it provides an accurate basis for the parameter setting of the motor module in Simulink, and also reveals the feasibility of changing the phase of the stator magnetic flux by directly controlling the stator voltage vector, and instantly adjusting the torque angle.

2.2 Core Principles of Direct Torque Control and Magnetic Flux Torque Regulation

The core of direct torque control lies in selecting the optimal voltage vector to make the stator magnetic flux rotate around the circumference and to adjust the angle between the magnetic flux and the rotor magnetic flux (torque angle δ) in real time. The calculation formula of electromagnetic torque Te indicates that the torque size is proportional to the product of the amplitude of the stator and rotor magnetic flux and the sine value of the torque angle. In the DTC system, the amplitude and position of the magnetic flux are estimated in real time by detecting the two-phase current and voltage of the stator. When the observed magnetic flux is lower than the given value, the voltage vector that can increase the magnetic flux should be selected; conversely, the opposite should be done. At the same time, the torque comparator generates a state signal to increase or decrease the torque based on the difference between the target torque and the actual torque. Although this "bang-bang" control logic is simple, it can make the stator magnetic flux respond fastest within each sampling period, enabling the stator magnetic flux to overcome load disturbances and always track the circular set trajectory, thereby achieving dynamic constant torque.

2.3 Division of Space Vector Sectors and Logical Derivation of Optimal Switch Table

Table 1. Direct Torque Control Optimal Voltage Vector Switching Lookup Table

Flux Error	Torque Error	Sector 1	Sector 2	Sector 3	Sector 4	Sector 5	Sector 6
$\phi = 1$ (Increase)	$\tau = 1$ (Increase)	V_2(110)	V_3(011)	V_4(011)	V_5(001)	V_6(101)	V_1(100)
$\phi = 1$ (Increase)	$\tau = -1$ (Decrease)	V_6(101)	V_1(100)	V_2(110)	V_3(010)	V_4(011)	V_5(001)
$\phi = -1$ (Decrease)	$\tau = 1$ (Increase)	V_3(011)	V_4(011)	V_5(001)	V_6(101)	V_1(100)	V_2(110)
$\phi = -1$ (Decrease)	$\tau = -1$ (Decrease)	V_5(001)	V_6(101)	V_1(100)	V_2(110)	V_3(010)	V_4(011)

To precisely control the direction of the stator magnetic flux, the magnetic flux plane is usually divided into six symmetrical sectors (Sector), each with a span of 60 degrees. Among the six non-zero voltage vectors (V1-V6) generated by the inverter, each vector has different effects on torque and magnetic flux in different sectors. For example, when the stator magnetic flux is in the first sector and needs to increase the magnetic flux and increase the torque, the system should select the V2 vector. This paper through logical regression analysis, details the optimal voltage switch selection strategies for the six sectors in the four combinations of magnetic flux increase and decrease and torque increase and decrease (as shown in Table 1). Additionally, the introduction of the zero vector is crucial for suppressing torque pulsation at low speeds. Through the mathematical abstraction of this nonlinear control logic, this paper constructs a controller module based on logical lookup table in the simulation, ensuring that the system can output the most favorable switching signals for maintaining a constant magnetic flux and responding to torque at any instantaneous state.

3. Design and Implementation of the MATLAB/Simulink Simulation System

3.1 Overall Architecture and Design of the Power Electronic Converter

In the MATLAB R2022b environment, this paper constructs a closed-loop system consisting of an asynchronous motor module, a three-phase voltage source inverter, a DTC core controller, and a feedback measurement section. The inverter part adopts the Universal Bridge module, configured as an IGBT/Diode structure, and driven by the six PWM signals output by the DTC controller. To enhance the authenticity of the simulation, the DC bus voltage on the DC side is set to 540V, corresponding to the industrial three-phase 380V AC rectification condition. In the solver settings of Simulink, the ode23tb rigid algorithm is selected, and the maximum step size is set to 1×10^(-6) seconds to capture the electromagnetic transient process caused by high-frequency switching actions. The overall architecture follows the modular design principle, encapsulating complex mathematical operations in Subsystems, achieving a clear separation of signal flow and energy flow, providing a physical basis for studying system energy feedback and dynamic losses.

3.2 Implementation of the Flux Observer and Torque Calculation Module

The accuracy of flux observation is the soul of the DTC system. This paper adopts the voltage model method (U-I model) to implement flux estimation. In the simulation model, by collecting the stator two-phase voltage and current signals, the flux is calculated using the integral link ψs = ∫(us - is Rs)dt. To overcome the DC drift and initial value problems caused by the pure integrator, a low-pass filter (LPF) is introduced in the simulation to replace the pure integrator, and phase and amplitude compensation is performed. The torque calculation module is based on the calculated flux and the measured current, and performs real-time calculation according to Te = 1.5p(ψα iβ - ψβ iα). The depth of this module lies in the precise control of the discrete sampling time. By adding a unit delay unit (Unit Delay) in Simulink, the calculation delay of the digital control system is simulated, making the simulation results closer to engineering reality.

3.3 Design Details of the Hysteresis Comparator and Sector Identification

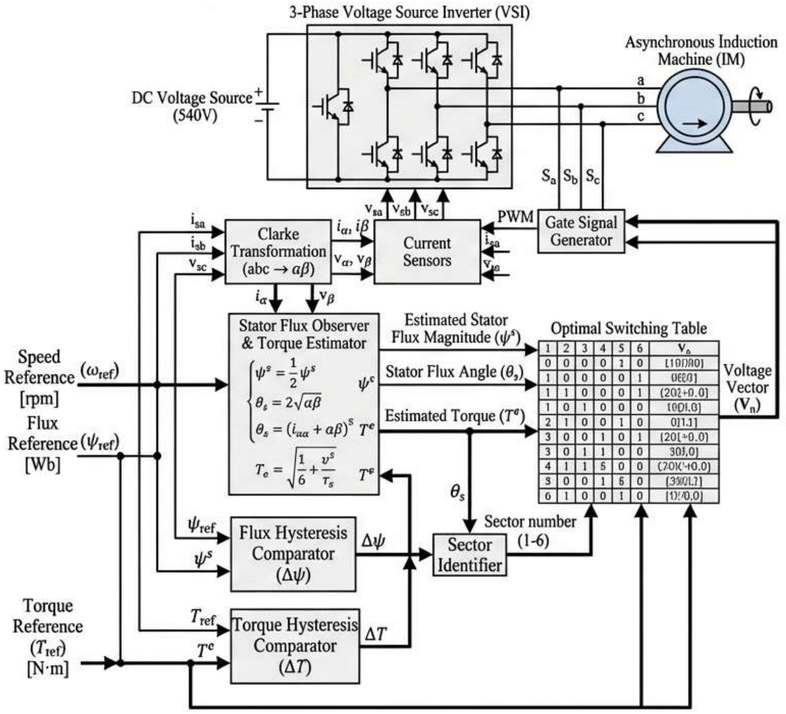


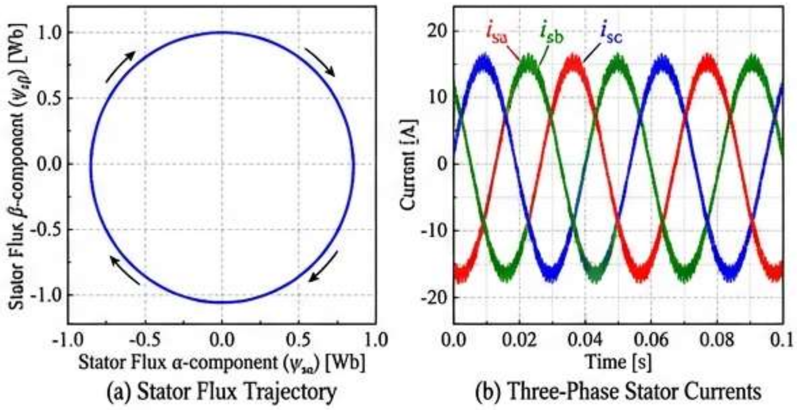
Figure 1. Overall logic block diagram of the direct torque control system for asynchronous motors based on Simulink

The design of the hysteresis comparator determines the switching frequency and the size of the torque pulsation. In the simulation, the flux ring hysteresis bandwidth is set to 1% of the set value, and the torque ring bandwidth is set to 2% of the rated torque. The sector identification module uses the arctan(ψβ/ψα) function to determine the current angle of the flux vector and combines multi-select logic to determine its sector. To prevent switching oscillation of the flux angle at the junction of each sector, a certain hysteresis coefficient is added to the simulation model. This refined algorithm design ensures the efficiency of the inverter switch state switching. During this process, an efficient lookup table algorithm is written using the MATLAB Function module to achieve the instantaneous output of the switching signals (Sa, Sb, Sc).

4. Analysis of Simulation Results and Evaluation of Control Performance

4.1 Analysis of Magnetic Flux Trajectory and Torque Ripple in Steady-State Operation

After the system enters steady-state operation, the trajectory of the stator magnetic flux in the α-β coordinate system is observed through the Scope module. The simulation results show that the magnetic flux trajectory presents a very smooth circular shape, with amplitude fluctuations controlled within a very small range. This indicates that the voltage model observer can effectively suppress integral drift and ensures the constant magnetic field strength. However, when observing the electromagnetic torque waveform, obvious sawtooth pulsations can be noticed, which is caused by the inherent switching logic of the hysteresis control. Through FFT analysis of the torque waveform, it is found that although DTC provides extremely fast response, its harmonic energy distribution is relatively wide. To further optimize, in the simulation experiment, by reducing the hysteresis bandwidth, it was discovered that although the pulsation was reduced, the switching frequency significantly increased, increasing the system's switching loss. Quantitative analysis revealed the balance game between DTC performance and efficiency.



(a) Stator Flux Trajectory (b) Three-Phase Stator Currents

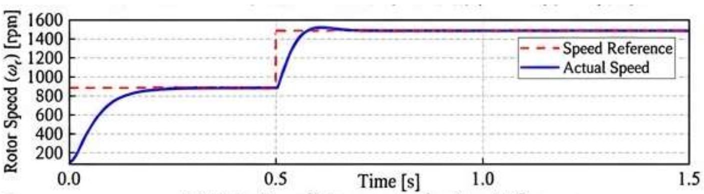
Figure 2. Synchronous flux trajectory (left) and steady-state current waveform (right) simulation diagram

4.2 Dynamic Response and Load Disturbance Resistance Capability Test

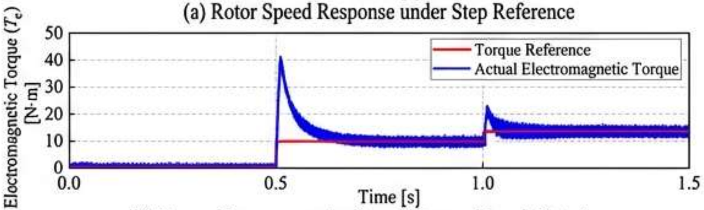
To verify the dynamic performance of the system, this paper designs two sets of comparative experiments: speed step experiment and load sudden change experiment. At t = 0.5s, the given speed of the motor is suddenly increased from 1000 rpm to 1500 rpm. The waveform shows that the torque reaches the limit value instantly and drives the rotor to accelerate rapidly. The speed rise process has almost no overshoot, and the establishment time is only 0.08s. At t = 1.0s, a 10 N·m load torque is suddenly applied to the motor. The system speed only shows a very small drop and quickly recovers. The torque feedback value can instantly track the load change, demonstrating that direct torque control still has strong disturbance resistance capability without the need for speed loop decoupling. This in-depth test proves the superiority of DTC in frequent acceleration and deceleration conditions, especially suitable for lifting or traction scenarios that require instantaneous high torque output.

4.3 Horizontal Comparison and Summary with Vector Control Performance

The DTC simulation results of this paper are compared with the standard rotor field-oriented vector control FOC. It can be seen that there are differences between the two. FOC has smaller current harmonics and relatively stable torque under steady-state conditions, but during acceleration, due to the limiting and saturation effect of the PI regulator, its response speed is slower than DTC. If the motor parameters are manually adjusted, for example, increasing the rotor resistance by 50%, the speed of the FOC system will fluctuate greatly, even causing loss of synchronization. The DTC system in this paper because its stator flux control does not rely on rotor parameters, the waveform has almost no change. This fully demonstrates the application prospect of DTC in parameter-sensitive applications. Through a comprehensive evaluation of the simulation process, it is believed that DTC technology is one of the main solutions to the dynamic response problem of asynchronous motors.



(a) Rotor Speed Response under Step Reference



(b) Torque Response under Speed Step and Load Disturbance

Figure 3. Speed Step Response Curve and Torque Dynamic Tracking Waveform Diagram

5. Conclusion

This paper uses MATLAB and Simulink to conduct simulation analysis on the direct torque control (DTC) system of asynchronous motors. Through the process from theoretical derivation to modeling practice, the overall control mechanism is analyzed. The research shows that by using the flux observer based on the U-I model and the optimal switching table, asynchronous motors can have excellent dynamic following performance and robustness. Hysteresis control will cause torque pulsation and switching noise. Due to the simple structure of the control method and its independence from the motor rotor parameters during operation, it has an irreplaceable position in industrial scenarios, especially for high dynamic performance requirements. The simulation model is highly accurate and logically rigorous. This paper analyzes various working conditions to provide data support for the development of high-performance AC frequency converter algorithms. Future research can combine space vector modulation and artificial intelligence control algorithms to maintain the dynamic advantages of DTC, completely eliminate torque pulsation, and enable AC speed regulation technology to achieve a comprehensive upgrade to full intelligence.

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