

SPACE VECTOR MODULATION–BASED DIRECT TORQUE CONTROL (DTC-SVM) FOR ROBOTIC APPLICATIONS

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Abstract: Space-Vector Modulated Direct Torque Control (DTC-SVM) is an advanced motor control strategy that combines the fast dynamic response of classical Direct Torque Control (DTC) with the fixed switching frequency and reduced torque ripple characteristics of Space Vector Modulation (SVM). In robotic systems, where high precision, smooth torque production, and rapid transient response are critical, DTC-SVM has emerged as a promising control approach for electric drives used in robotic joints and actuators. This paper presents a comprehensive review and analytical study of DTC-SVM applied to robotics. The theoretical foundations of DTC and SVM are discussed, followed by the formulation of DTC-SVM. Its advantages over conventional DTC and Field-Oriented Control (FOC) are highlighted. Recent research trends, implementation challenges, and performance improvements in robotic applications are also reviewed.

Keywords: Direct Torque Control, Space Vector Modulation, Robotics, Electric Drives, Torque Ripple Reduction, Robotic Actuators

I. INTRODUCTION

Modern robotic systems demand high-performance electric drives capable of delivering accurate torque, fast dynamic response, and smooth motion under varying load conditions. Applications such as industrial manipulators, humanoid robots, autonomous mobile robots, and collaborative robots require precise control of speed and torque to achieve high accuracy and efficiency.

Direct Torque Control (DTC) is widely recognized for its simple structure, rapid torque response, and robustness against parameter variations. However, conventional DTC suffers from major drawbacks such as high torque ripple, variable switching frequency, and acoustic noise, which limit its suitability for high-precision robotic applications.

To overcome these limitations, Space-Vector Modulated Direct Torque Control (DTC-SVM) has been proposed. By replacing the hysteresis controllers and switching table of classical DTC with a space vector modulator, DTC-SVM achieves constant switching frequency, lower torque ripple, and improved steady-state performance. This paper focuses on the role of DTC-SVM

in robotics and evaluates its effectiveness compared to traditional control strategies.

2. ELECTRIC DRIVES IN ROBOTICS

An electric drive system in robotics converts electrical energy into precise mechanical motion using motors (like servos or steppers) and controls them via drivers/controllers, enabling robots to move joints, wheels, or end-effectors with high accuracy, speed, and repeatability, forming the core of robotic movement for tasks from small precise manipulations to heavy industrial operations, often favored over hydraulic/pneumatic systems due to better computer integration and efficiency.

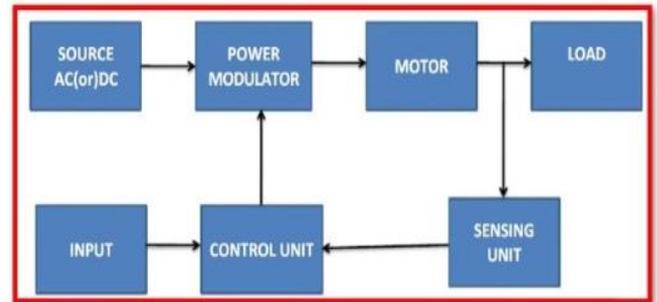


Fig. 1 - Electrical drive's block diagram

2.1 Components of Electric Drives: -

The power modulator, motor, controlling unit, & sensing units are the main components of electrical drives.

1. Power Source
2. Power Modulator
3. Control Unit
4. Sensing Unit
5. Electric Motor and
6. Load

2.1 Role of Motor Control in Robotic Systems

Motor control is crucial in robotics for translating commands into precise, efficient, and reliable physical motion, enabling robots to perform tasks by managing motor speed, torque, and position, using sensors for feedback to adapt to changing loads and environments, and ensuring smooth, accurate execution in everything from industrial arms to autonomous vehicles. It involves a system of controllers, drivers, and sensors to power actuators (motors) for accurate movement, stability, and energy efficiency, forming the core of robotic action

Electric motors such as induction motors (IM), permanent magnet synchronous motors (PMSM), and brushless DC motors (BLDC) are commonly used in robotic joints and actuators. The performance of a robotic system heavily depends on the quality of motor control, which directly affects:-

- Position accuracy
- Torque smoothness
- Energy efficiency
- Dynamic response

2.2 Control Requirements for Robotic Actuators

Robotic drives must satisfy stringent requirements, including:

- Fast torque response for dynamic motion
- Low torque ripple for smooth movement
- High efficiency over a wide speed range
- Robustness to load disturbances and parameter variations

DTC-SVM is well suited to meet these requirements, making it attractive for advanced robotic applications.

3. FUNDAMENTALS OF DIRECT TORQUE CONTROL (DTC)

3.1 Principle of DTC

Direct Torque Control directly regulates the electromagnetic torque and stator flux of the motor by selecting appropriate inverter switching states. Unlike Field-Oriented Control (FOC), DTC does not require coordinate transformations or current regulators.

The electromagnetic torque of an AC motor can be expressed as:

$$T_e = \frac{3}{2}p(\psi_s \times i_s)$$

where: -

- p is the number of pole pairs

- ψ_s is the stator flux vector
- i_s is the stator current vector

3.2 Limitations of Conventional DTC

Despite its advantages, classical DTC has several drawbacks:

- High torque and flux ripples
- Variable switching frequency
- Difficulty in low-speed operation

These issues are particularly problematic in robotic systems that require smooth and precise motion.

4. SPACE VECTOR MODULATION (SVM)

Space Vector Modulation is a digital modulation technique used in voltage source inverters (VSI) to generate sinusoidal output voltages with optimal utilization of the DC bus.

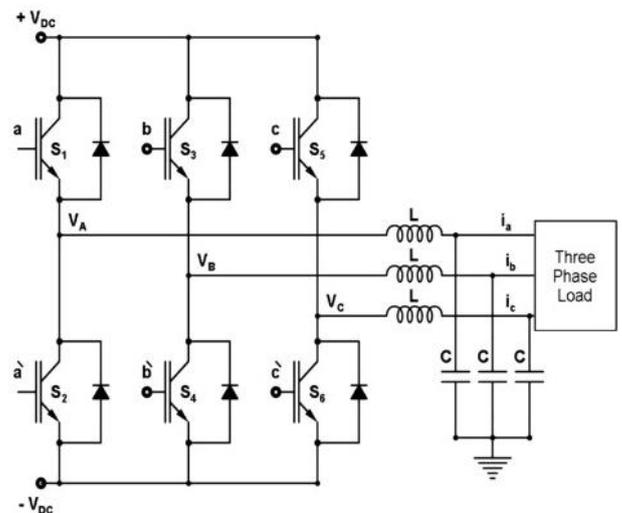


Fig.2- Space Vector Modulation is a digital modulation technique used in voltage source inverters (VSI)

Key advantages of SVM include:

- Fixed switching frequency
- Lower harmonic distortion
- Improved DC bus voltage utilization

In SVM, the reference voltage vector is synthesized by combining adjacent active vectors and zero vectors within a sampling period.

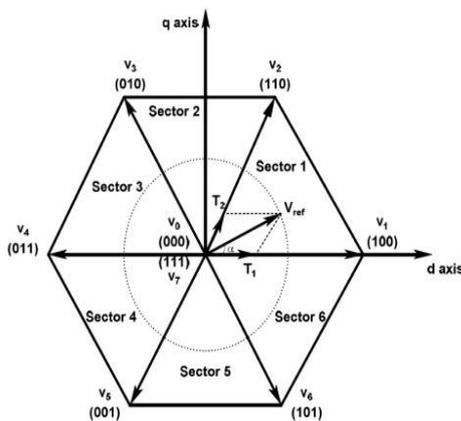


Fig.3: - Output voltage space of the two-level inverter in dq coordinates.

5. SPACE-VECTOR MODULATED DIRECT TORQUE CONTROL (DTC-SVM)

5.1 Concept of DTC-SVM

DTC-SVM integrates the DTC concept with SVM by replacing hysteresis controllers with PI or predictive controllers that generate a reference voltage vector. This reference vector is then applied to the inverter using SVM.

5.2 Control Structure

The basic blocks of a DTC-SVM system include:

- Torque and flux estimators
- Torque and flux controllers
- Reference voltage vector calculator
- Space Vector Modulation inverter

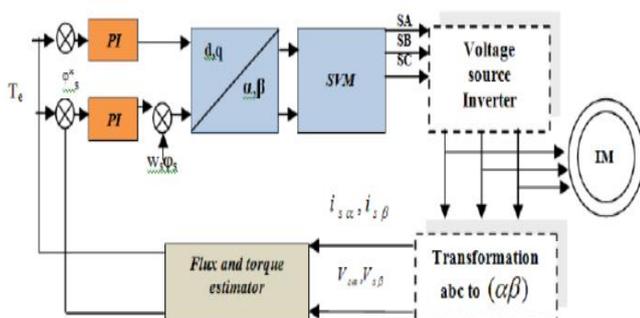


Fig. 4 - Block diagram of DTC-SVM

5.3 Mathematical Formulation

The reference stator voltage vector is computed as:

$$\vec{V}_s^* = R_s \vec{i}_s + \frac{d\vec{\psi}_s}{dt}$$

where:

- R_s is stator resistance
- i_s is stator current
- ψ_s is stator flux

This voltage vector is synthesized using SVM to achieve the desired torque and flux control.

6. APPLICATION OF DTC-SVM IN ROBOTICS

6.1 Robotic Manipulators

In multi-degree-of-freedom robotic arms, DTC-SVM provides smooth torque control at each joint, reducing vibration and improving end-effectors accuracy.

6.2 Mobile Robots

For autonomous mobile robots, DTC-SVM ensures fast torque response and stable speed control, especially during acceleration, deceleration, and load changes.

6.3 Humanoid and Collaborative Robots

Humanoid and collaborative robots require safe and smooth interaction with humans. The low torque ripple and precise control offered by DTC-SVM enhance compliance and safety.

7. PERFORMANCE COMPARISON

Compared to classical DTC and FOC, DTC-SVM offers:

- Lower torque ripple
- Constant switching frequency
- Improved low-speed performance
- Reduced acoustic noise

These features make DTC-SVM particularly suitable for precision robotics.

8. RECENT RESEARCH TRENDS

Recent studies focus on:

- Model Predictive DTC-SVM
- AI and fuzzy-logic-based DTC-SVM

- Sensorless DTC-SVM for robotic drives
- Energy-efficient control strategies

Integration of intelligent control techniques further enhances the performance of DTC-SVM in robotics.

9. CHALLENGES AND FUTURE SCOPE

Despite its advantages, DTC-SVM faces challenges such as:

- Increased computational complexity
- Accurate flux and torque estimation at low speeds

Future research may explore:

- Real-time implementation on FPGA and DSP
- Hybrid control strategies
- Application in soft robotics and exoskeletons

10. CONCLUSION

Space-Vector Modulated Direct Torque Control is a powerful and efficient motor control strategy for robotic applications. By combining the simplicity and fast response of DTC with the smooth operation of SVM, DTC-SVM addresses the limitations of conventional DTC and meets the stringent demands of modern robotics. Ongoing research and technological advancements are expected to further expand its application in next-generation robotic systems.

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