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Low-ripple direct torque control for induction motor drive systems: a review of torque and flux regulation, modulation strategies, and advanced control techniques

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ABSTRACT

Direct torque control (DTC) is valued in induction motor drives for its fast torque response, simple structure, and direct regulation of stator flux and electromagnetic torque. However, conventional hysteresis-based DTC produces appreciable torque and flux ripple, variable switching frequency, and degraded low-speed performance. These effects arise from discrete voltage-vector selection, finite sampling intervals, flux-estimation errors, and the interaction between torque and flux dynamics. This review examines methods developed to reduce these limitations, including space-vector-modulated DTC, constant-frequency switching, duty-ratio control, multilevel converters, predictive torque control, fuzzy and neural approaches, and robust sliding-mode techniques. The comparison considers ripple attenuation, transient response, switching losses, computational demand, parameter sensitivity, and experimental validation. The literature indicates that fixed-frequency modulation and optimized vector sequences can substantially improve steady-state waveform quality, while predictive and intelligent methods offer additional flexibility under changing operating conditions. Nevertheless, gains reported in simulation do not always translate directly to embedded hardware because of sampling delay, model mismatch, sensor noise, and computational constraints. The review identifies priorities in standardized benchmarking, low-speed flux estimation, multi-objective control, and real-time experimental validation for industrial and transportation drive applications.

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1. INTRODUCTION

Induction motors are widely used in industrial machinery, electric transportation, pumps, compressors, and variable-speed drive applications because of their robust construction and relatively simple maintenance requirements. Their performance in high-dynamic applications depends strongly on the ability of the drive controller to regulate electromagnetic torque and magnetic flux accurately. Direct torque control (DTC) was developed to provide rapid torque response through direct manipulation of the inverter switching states. Its relatively simple structure and reduced dependence on coordinate transformations have made it an important alternative to conventional field-oriented control [1]–[5].

Despite these advantages, conventional DTC has an important limitation involving torque and stator-flux ripple. The conventional arrangement uses hysteresis comparators and a switching table to select voltage vectors according to torque and flux errors. Since the available voltage vectors are discrete, the controller cannot always produce the exact voltage required to maintain the commanded torque and flux values. Consequently, the electromagnetic torque and stator-flux magnitude fluctuate around their references, while the inverter switching frequency varies with operating conditions [3], [4], [6].

These fluctuations can increase acoustic noise, mechanical vibration, current harmonics, and additional losses in the motor and inverter. The problem becomes particularly important at low speed, where stator resistance and flux-estimation errors can significantly influence the accuracy of the control process. Several research approaches have therefore been developed to improve voltage-vector selection, regulate switching frequency, and enhance the estimation of motor variables. This review evaluates these developments and identifies the technical compromises associated with achieving low torque and flux ripple simultaneously [7]–[10].

2. CONVENTIONAL DTC ARCHITECTURE AND RIPPLE FORMATION

Conventional DTC estimates stator flux and electromagnetic torque from measured stator voltages and currents. The estimated quantities are compared with their respective references, and hysteresis controllers determine whether the torque and flux errors should increase, decrease, or remain within their acceptable bands. A switching table then selects the inverter voltage vector according to the flux sector and comparator outputs. This approach provides a direct control mechanism without requiring a separate current-regulation loop [1], [2], [4].

The main source of ripple is the mismatch between the required motor voltage and the finite set of voltage vectors available from a conventional two-level inverter. A selected active vector may increase torque rapidly but also produce an undesirable change in flux magnitude. Similarly, a zero vector may help regulate flux while providing insufficient torque correction under certain operating conditions. The resulting interaction between torque and flux regulation produces a characteristic ripple pattern that depends on motor speed, load, DC-link voltage, and hysteresis-band settings [6], [8], [11].

Switching-frequency variation is another important consequence of hysteresis-based control. The switching frequency depends on how quickly the torque and flux trajectories cross their hysteresis boundaries, which changes with the operating point and motor parameters. At low speed, the switching pattern can become irregular and may produce audible noise or unfavorable current harmonics. Consequently, reducing ripple requires consideration of switching frequency and inverter losses rather than simply narrowing the hysteresis bands [12]–[15].

3. SPACE VECTOR MODULATION AND CONSTANT-FREQUENCY DTC

Space vector modulation (SVM) is an established approach for improving the steady-state performance of DTC. Instead of selecting a single inverter switching state directly from a conventional switching table, DTC-SVM calculates a reference voltage vector and synthesizes it using appropriate inverter switching sequences. This approach enables more precise control of the average voltage applied during each sampling interval. It also provides a relatively constant switching frequency, which can improve current quality and reduce torque and flux oscillations [3], [16], [17].

Constant-frequency DTC techniques have been developed to address the irregular switching behavior of conventional hysteresis control. These methods include modified hysteresis bands, duty-cycle regulation, and carrier-based modulation. The work of Idris and Yatim established a strategy for reducing torque ripple while imposing a constant switching frequency. Subsequent studies developed band-constrained and modified torque-control approaches to improve the relationship between ripple magnitude and inverter switching behavior [7], [8], [12].

SVM-based DTC nevertheless requires additional calculations compared with conventional switching-table control. The controller must determine the appropriate reference voltage, switching sequence, and dwell time while accounting for sampling and inverter constraints. At high switching frequencies, the computational burden can become significant for low-cost embedded controllers. Therefore, the practical selection between conventional DTC and DTC-SVM should consider the required ripple performance, processor capability, and power-converter rating [14], [15], [18].

4. PREDICTIVE AND DUTY-RATIO-BASED DTC

Predictive torque control improves voltage-vector selection by estimating the future behavior of torque and flux under candidate inverter switching states. The controller evaluates the predicted responses and selects the voltage vector that minimizes a defined control objective. This approach can directly incorporate torque error, flux error, switching transitions, and operating constraints into the control decision. It therefore provides a flexible framework for reducing ripple while retaining the fast dynamic response associated with DTC [16], [17], [19].

Finite-control-set predictive torque control is particularly relevant because it evaluates the discrete voltage vectors available from the inverter. However, the number of candidate vectors and control objectives can increase computational requirements. Weighting-factor selection is another difficulty because torque and flux errors may have different scales and dynamic characteristics. Research on simplified predictive DTC, optimized weighting factors, and multi-objective predictive control has sought to reduce these implementation difficulties [18], [20]–[23].

Duty-ratio-based methods provide another means of improving the average voltage applied during each switching interval. Instead of applying a selected active voltage vector for the entire control period, the controller determines the duration of active and zero-vector application. This can reduce torque and flux deviations while preserving the direct-control structure. Research on predictive and duty-ratio-based approaches indicates that their performance depends on accurate prediction, suitable vector selection, and the ability to compensate for digital implementation delays [19], [21], [24].

5. MULTILEVEL AND ADVANCED INVERTER-BASED DTC

Multilevel inverters provide additional voltage vectors that can improve the resolution of torque and flux regulation. A larger number of available voltage levels enables the controller to select smaller voltage increments, potentially reducing the oscillations associated with conventional two-level DTC. This advantage is especially relevant for high-power drives operating at relatively low switching frequencies. Research on three-level and multilevel inverter-fed induction motors has demonstrated the potential of these structures for improving torque regulation [10], [13], [25].

Open-end winding induction motor configurations provide another opportunity for expanding the available voltage-vector set. Dual-inverter arrangements can generate additional voltage combinations, allowing more flexible control of stator flux and electromagnetic torque. Modified lookup tables and optimized switching sequences have been investigated to improve the performance of these systems. However, additional inverter hardware can increase cost, control complexity, and DC-link balancing requirements [26].

The use of more voltage vectors does not automatically guarantee lower ripple under every operating condition. The controller must select suitable vectors while avoiding excessive switching transitions and unwanted common-mode voltage. Multilevel systems may also require capacitor-voltage balancing and more complicated protection strategies. Therefore, converter topology and DTC algorithm should be designed together to achieve meaningful improvements in waveform quality and overall drive efficiency [10], [13], [25], [26].

6. INTELLIGENT, FUZZY, NEURAL, AND ROBUST DTC

Intelligent control methods have been investigated to improve the adaptability of DTC under nonlinear and changing operating conditions. Fuzzy logic can replace conventional hysteresis comparators or modify the switching decision according to torque and flux errors. It can also support speed regulation and flux estimation when accurate motor parameters are unavailable. Neuro-fuzzy DTC was explored in early research, while more recent studies have investigated fuzzy prediction and adaptive switching strategies [9], [27], [28].

Artificial neural networks offer an alternative method for selecting inverter switching states. A trained network can approximate the decision process of a conventional switching table while incorporating nonlinear relationships between measured variables and desired control actions. Recent FPGA-based work has demonstrated the implementation of neural-network-based DTC for induction machines, with attention to reducing torque and stator-flux ripple. Nevertheless, neural controllers require representative training data, appropriate validation, and careful consideration of hardware resource utilization [29], [30].

Sliding-mode control and fractional-order approaches provide another route to robust torque and flux regulation. Their principal advantage is the ability to maintain acceptable control performance in the presence of disturbances and parameter uncertainty. However, conventional sliding-mode control may introduce chattering, which can affect switching behavior and current quality. Combining sliding-mode control with DTC and suitable modulation techniques can reduce these effects, although the resulting controller requires careful tuning and experimental assessment [31], [32].

7. COMPARATIVE ASSESSMENT OF RIPPLE-REDUCTION STRATEGIES

Table 1 summarizes the principal DTC approaches and their expected contributions to torque and flux ripple reduction. It also highlights the main implementation limitations associated with each technique. The comparison indicates that no single method provides the best performance under all operating

conditions. Consequently, the selection of a low-ripple DTC strategy should be based on the required dynamic response, switching frequency, motor rating, and available digital-control hardware.

Table 1. Comparative assessment of low-ripple DTC techniques for induction motor drives

DTC strategy	Main ripple-reduction mechanism	Main advantages	Main limitations
Conventional hysteresis DTC	Direct voltage-vector selection	Simple structure and fast response	High ripple and variable switching frequency
Modified hysteresis DTC	Adjusted comparator bands and switching logic	Low implementation complexity	Ripple performance depends on operating conditions
DTC-SVM	Reference voltage-vector synthesis	Constant switching frequency and improved waveform quality	Higher computational requirement
Duty-ratio DTC	Optimized active and zero-vector duration	Better average torque and flux regulation	Sensitive to dwell-time calculation
Predictive DTC	Future-state prediction and vector optimization	Flexible multi-objective control	Model dependence and computation burden
Multilevel DTC	Additional voltage-vector resolution	Lower voltage steps and potential ripple reduction	More switches and balancing requirements
Fuzzy DTC	Rule-based nonlinear control	Adaptability and reduced dependence on fixed thresholds	Rule design and tuning complexity
Neural-network DTC	Learned switching-state selection	Nonlinear decision capability and hardware implementation potential	Training, generalization, and validation requirements
Sliding-mode DTC	Robust switching or modulation control	Disturbance rejection and parameter robustness	Chattering and tuning requirements

Comparative studies show that improvements in torque ripple may not always produce equivalent improvements in flux ripple or current distortion. For example, a controller optimized mainly for torque tracking may select voltage vectors that increase flux oscillations. Similarly, increasing switching frequency can improve waveform quality but may increase inverter switching losses and thermal stress. A meaningful comparison should therefore include torque ripple, flux ripple, current THD, switching frequency, efficiency, transient response, and computational time [14], [18], [20], [24], [33].

8. RECENT DEVELOPMENTS AND RESEARCH CHALLENGES

Research published through 2023 increasingly emphasizes combined approaches rather than isolated modifications to conventional switching tables. Optimization algorithms have been used to select stator-flux references and improve torque regulation in electric-vehicle-oriented induction motor drives. Other studies have investigated fractional-order sliding-mode DTC, fuzzy flux estimation, and neural switching-state selection. These developments indicate a broader movement toward adaptive control architectures that address torque ripple, flux ripple, current harmonics, and robustness together [30]–[35].

Experimental validation remains an important challenge because simulated improvements may be affected by sampling delay, sensor noise, inverter dead time, and motor parameter variation when implemented in real hardware. FPGA-based hardware-in-the-loop studies provide useful evidence of real-time feasibility, but they do not automatically establish long-term performance in industrial operating environments. Experimental investigations should therefore include multiple speed regions, load disturbances, low-speed operation, and parameter variations. The measurement procedure should also distinguish steady-state ripple from transient torque deviations [29], [30], [34].

Another research priority is the development of consistent performance benchmarks for different DTC architectures. Published studies frequently use different motor ratings, DC-link voltages, sampling frequencies, ripple definitions, and load conditions. These differences make it difficult to determine whether one strategy is objectively superior to another. Future research should adopt common test conditions and report both control performance and implementation cost, including processor utilization, switching losses, and thermal behavior [15], [23], [33], [36]–[39].

9. CONCLUSION

Conventional DTC provides fast electromagnetic torque response and a relatively simple structure for induction motor drives, but its hysteresis-based switching mechanism produces significant torque and stator-flux ripple. The main causes are discrete voltage-vector selection, variable switching frequency, finite sampling intervals, and inaccuracies in flux estimation. Research has addressed these limitations through SVM, constant-frequency switching, predictive control, duty-ratio regulation, multilevel inverters, and

intelligent control methods. These approaches provide different compromises between waveform quality, dynamic performance, switching losses, and implementation complexity.

The reviewed literature indicates that DTC-SVM and optimized voltage-vector sequences are effective options for improving steady-state torque and flux regulation. Predictive and intelligent methods offer greater flexibility when several control objectives or changing operating conditions must be considered. Nevertheless, their advantages depend on model accuracy, computational capability, and hardware validation. Future work should prioritize simultaneous torque and flux ripple minimization, robust low-speed operation, standardized experimental benchmarking, and real-time implementation suitable for industrial and transportation applications.

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