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Direct Torque Control and Sensor-less Speed Estimation for Multiphase Induction Motor Drives: A Review

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Abstract— *Multiphase induction motor drives, and in particular the asymmetrical six-phase (split-phase) induction motor, have become an established alternative to three-phase drives in high-power and safety-critical applications such as electric ships, more-electric aircraft, traction, and electric vehicles, owing to their reduced per-phase current stress, lower torque pulsation, and inherent fault-tolerant operation. This paper reviews the literature on the control of multiphase induction motor drives, with a specific focus on Direct Torque Control (DTC) and encoder-less (sensor-less) rotor-speed estimation. The modelling of the six-phase machine using Vector Space Decomposition is first summarized, followed by a structured review of scalar, vector, and direct-torque control strategies, with emphasis on the x–y plane harmonic-excitation problem that arises when three-phase-style DTC switching tables are extended to six-phase inverters, and the modified switching-table and DTC-SVM schemes proposed to address it. The paper then reviews encoder-less speed-estimation techniques — signal injection, Model Reference Adaptive System (MRAS), Kalman filtering, and Sliding Mode Observers (SMO), including reaching-law refinements such as the Constant Rate Reaching Law and its optimized variants — together with online stator-resistance adaptation for maintaining low-speed accuracy. Representative works are compared and summarized in tabular form, and open research challenges are identified for harmonic-aware DTC design and robust, computationally efficient sensor-less estimation for multiphase drives.*

Keywords— Multiphase induction motor, six-phase drive, Direct Torque Control, Sliding Mode Observer, MRAS, sensor-less control, vector space decomposition, torque ripple.

I. INTRODUCTION

Electric motor drives underpin nearly all modern industrial, transportation, and defence systems, and the three-phase induction motor has traditionally dominated variable-speed applications because of its robustness, simplicity, and well-established control theory [4], [6]. As power ratings rise and applications move into safety-critical domains — electric ships, more-electric aircraft, traction, and electric vehicles — the limitations of the three-phase machine become significant: per-phase current and inverter-leg current rating increase with power level, and the loss of a single phase disables the drive entirely [1], [8]. Multiphase (more than three-phase) drives directly address these limitations by distributing the same power over a larger number of phases, reducing per-phase and per-leg current for a given rating, lowering torque pulsation, and — uniquely among AC machine types — retaining a balanced rotating field, and hence continued operation, following the loss of one or more phases [4], [6], [12].

Among multiphase configurations, the asymmetrical (split-phase) six-phase induction motor, obtained by displacing two three-phase winding sets by 30 electrical degrees, has received the most attention because this displacement suppresses the sixth-harmonic torque pulsation present in the symmetrical (60°-shifted) configuration [13], [14]. Two broad control philosophies have been applied to such machines: field-oriented (vector) control, and Direct Torque Control (DTC). DTC, in particular, dispenses with inner current-control loops and instead regulates stator flux and torque directly through hysteresis comparators and a switching look-up table, giving fast torque dynamics with a structurally simple controller [2], [7], [18]. Extending DTC from three to six phases, however, is not a trivial exercise: the six-phase inverter's much larger voltage-vector set introduces a non-flux/torque-producing x–y subspace, and an unmodified switching table excites this subspace, producing 6k ± 1 order stator current harmonics that increase machine losses without contributing to torque [17], [20], [23].

A second, largely independent line of research addresses the elimination of the physical speed sensor. Both vector control and DTC conventionally require a rotor speed or position sensor for closed-loop operation; such sensors add cost, wiring complexity, and a failure-prone mechanical component and are frequently impractical in harsh operating environments [26], [30]. This has driven extensive research into model-based, encoder-less (sensor-less) speed-estimation techniques, of which Model Reference Adaptive Systems, Kalman filters, and Sliding Mode Observers are the most widely reported [27]–[39].

This paper reviews both lines of research as they apply specifically to multiphase, and particularly six-phase, induction motor drives. Section II summarizes multiphase machine fundamentals and the Vector Space Decomposition (VSD) modelling approach that underlies most of the literature discussed. Section III reviews control strategies for multiphase drives. Section IV focuses on modified switching-table and DTC-SVM schemes proposed to mitigate x–y harmonic excitation. Section V reviews encoder-less speed-estimation techniques, with particular attention to sliding-mode observers and reaching-law design. Section VI reviews online parameter-estimation methods used to sustain observer accuracy at low speed. Section VII presents a consolidated comparative discussion and identifies open research challenges, and Section VIII concludes the paper.

II. MULTIPHASE INDUCTION MOTOR DRIVES: FUNDAMENTALS

A. Why Multiphase?

Comparative studies of multiphase and three-phase machines consistently report four principal advantages of the multiphase configuration for a given power rating: (i) reduced per-phase current and inverter-leg current, permitting the use of lower-current-rated, lower-cost power semiconductor devices [4], [6]; (ii) reduced torque pulsation, since the fundamental pulsation frequency scales with the number of phases [13]; (iii) reduced rotor harmonic copper loss [6], [12]; and (iv) inherent post-fault operating capability — a multiphase machine can sustain a balanced rotating field with a reduced number of healthy phases, a property unavailable to a three-phase machine [4], [8]. These properties have motivated the study of machines with five, six, seven, nine, eleven, and even twelve phases [10], [11], although the six-phase (dual three-phase) configuration remains the most widely adopted in practice because it can be realized by re-winding a conventional three-phase stator and driven by two standard three-phase inverter bridges [14], [15].

Within the six-phase family, the asymmetrical (30°-shifted) winding arrangement is generally preferred over the symmetrical (60°-shifted) arrangement because the 30° displacement cancels the sixth-harmonic torque component that is otherwise dominant in six-phase machines, giving a significantly smoother torque profile [13], [14]. This asymmetrical machine — referred to in the literature variously as the SPAIM (split-phase asymmetrical induction motor) or ASIM — is the configuration considered in the majority of the DTC and sensor-less-control literature reviewed in this paper.

B. Vector Space Decomposition (VSD) Modelling

The mathematical modelling of multiphase machines was substantially simplified by the introduction of the Vector Space Decomposition (VSD) approach [4], [6], which maps the six physical stator variables onto three orthogonal two-dimensional subspaces: the α–β subspace, in which flux and torque are produced; the x–y subspace, which does not contribute to flux or torque production but through which low-order (6k ± 1) stator current harmonics circulate; and the zero-sequence subspace, which carries no useful excitation in a star-connected, isolated-neutral machine. This decomposition is central to nearly all of the modified-DTC literature reviewed in Section IV, because it isolates, in a single pair of state variables, exactly the harmonic content that a well-designed switching strategy must suppress.

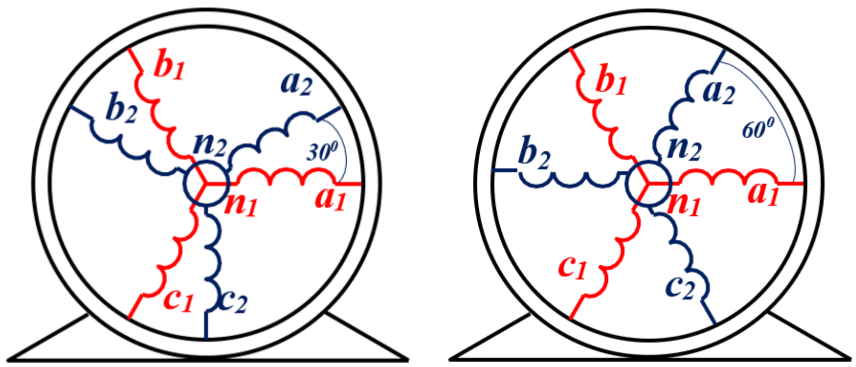

Fig. 1. Stator winding arrangement of an asymmetrical six-phase induction motor: (a) 30° spatial shift, (b) 60° spatial shift.

Once transformed into the rotating d–q–0 frame via VSD, the machine's per-unit voltage, flux-linkage, and electromagnetic torque equations take a form closely analogous to the familiar three-phase d–q model, differing principally in the presence of the second (x–y) stator current pair and its associated leakage terms [4], [14]. This structural similarity is what allows control techniques developed for three-phase machines — scalar control, field-oriented control, and DTC — to be extended, with appropriate modification, to the multiphase case, as reviewed next.

III. CONTROL STRATEGIES FOR MULTIPHASE DRIVES

A. Scalar and Field-Oriented (Vector) Control

Scalar (V/f) control remains the simplest approach to multiphase drive control, regulating only the magnitude of the applied voltage relative to frequency, but its open-loop nature gives poor dynamic performance and negligible torque control at low speed [6]. Field-oriented control (FOC), by contrast, decouples the flux- and torque-producing current components through the VSD/d–q transformation and a set of current-regulated PI controllers, and has been extended to five-, six-, and higher-phase machines with good reported dynamic performance [9], [26]. Its principal drawbacks — sensitivity to rotor parameter variation and the computational burden of nested current and speed control loops — are the main motivation for the DTC-based alternatives discussed next.

B. Classical (Three-Phase-Style) Direct Torque Control

Direct Torque Control, originally proposed by Takahashi and Noguchi for the three-phase machine, regulates stator flux magnitude and electromagnetic torque directly using hysteresis comparators and a fixed switching look-up table, avoiding the coordinate transformations and PWM modulator stage required by FOC [2], [18]. When extended directly to a six-phase inverter — selecting, at each sampling instant, a single large-magnitude voltage vector in the α–β plane based on the flux sector and the outputs of the flux/torque hysteresis comparators — this classical approach retains DTC's fast torque response, but does not account for the corresponding voltage this vector also applies in the x–y subspace [17], [18]. Because this excitation is not actively managed, low-order ($6k \pm 1$) stator current harmonics of appreciable magnitude appear, increasing machine losses, current distortion, and acoustic noise without contributing to torque production [17], [20]. This limitation is the central motivation for the modified DTC schemes reviewed in Section IV.

IV. MODIFIED SWITCHING-TABLE AND DTC-SVM SCHEMES

A substantial body of work has proposed modifications to the classical DTC switching table specifically to suppress x–y plane excitation in multiphase drives. Rakesh and Narayanan [17] investigated zero-sequence signal injection to improve harmonic performance in split-phase drives. Hatua and Ranganathan [18] proposed early switching-table schemes tailored to the split-phase machine. Suhel et al. [20] developed a modified switching table restricted to vectors with minimal x–y component, directly targeting harmonic suppression. Pandit et al. [22] introduced synthetic (virtual) voltage vectors, constructed as a time-weighted combination of two or more physical switching states, whose net x–y contribution cancels while the desired α–β effect is retained. Holakooie et al. extended this line of work with a five-dimensional switching table that simultaneously regulates flux, torque, and x–y current in a single decision step [23], a switching-table scheme with explicit x–y current regulation [24], and a virtual-subspace DTC strategy aimed specifically at torque-ripple minimization [25].

A parallel line of work replaces the fixed look-up table with space-vector modulation, giving DTC-SVM schemes that synthesize the commanded voltage vector directly rather than selecting it from a discrete table. Muduli et al. [21] proposed an SVPWM-based DTC scheme for a five-phase drive with explicit common-mode-voltage reduction, and Peter et al. [51] proposed a simplified DTC-SVPWM scheme using a single PI controller in place of separate flux and torque regulators. DTC-SVM schemes generally achieve lower current distortion and a fixed switching frequency at the cost of increased computational complexity relative to look-up-table DTC [21], [51]. Common-mode voltage, a related concern for winding-insulation and bearing stress, has itself been the subject of dedicated switching and modulation strategies for multiphase inverters [47]–[50].

Table I summarizes representative modified-DTC approaches and their reported strengths and limitations.

Approach	Mechanism	Reported strength / limitation
Zero-sequence signal injection [17]	Improves harmonic performance via injected zero-sequence signal	Requires additional signal generation and injection circuitry
Split-phase switching-table DTC [18]	Early switching-table formulation tailored to split-phase machine	Limited explicit x–y management
Large-vector-restricted	Restricts table to vectors with minimal	Reduced low-order harmonics;

switching table [20]	x–y component	coarser voltage resolution
Synthetic (virtual) vectors [22]	Combines two or more states so net x–y voltage cancels	Additional timing computation per sample
Five-dimensional switching table [23]	Simultaneous flux/torque/x–y regulation in one table	Higher table dimensionality and design complexity
Switching table with x–y current regulation [24]	Direct closed-loop regulation of x–y current	Requires an additional current-error hysteresis loop
Virtual-subspace DTC [25]	Targets torque-ripple minimization via virtual subspace	Ripple-focused; harmonic suppression is a secondary benefit
DTC-SVM (five-phase, CMV-aware) [21]	SVM-synthesized vector with common-mode voltage reduction	Fixed switching frequency; higher computational cost
Simplified DTC-SVPWM, single PI [51]	Single PI controller replaces separate flux/torque regulators	Simplifies structure; tuning trade-off between flux and torque response

Table I. Representative modified DTC / DTC-SVM schemes for multiphase drives.

V. ENCODER-LESS (SENSOR-LESS) SPEED ESTIMATION

Eliminating the physical speed sensor removes cost, wiring, and a failure-prone mechanical component, and is particularly valuable in harsh or inaccessible operating environments such as submersible pumps, marine propulsion, and traction [26], [30], [31]. This section reviews the four dominant families of encoder-less estimation technique reported for induction motor drives, three of which have been specifically extended to multiphase machines.

A. Signal Injection

Signal-injection methods estimate rotor position from the machine's magnetic saliency by superimposing a high- or low-frequency test signal on the fundamental excitation and extracting position information from the resulting current response. These methods perform well at zero and very low speed, where back-EMF-based methods are inherently weak, but require additional signal processing and can introduce acoustic noise and extra torque ripple [6].

B. Model Reference Adaptive System (MRAS)

MRAS-based observers compare the output of a reference (voltage) model and an adjustable (current) model of the machine and drive their difference to zero through an adaptation law, typically a PI controller, to estimate rotor speed. Hamed et al. [27] proposed a new MRAS formulation for motor speed estimation, while Das et al. [28] used the machine's d– and q-axis circuit impedances as the MRAS functional candidate. Reddy et al. [29] proposed a modified stator-current-error-based MRAS specifically for DTC-controlled drives. For multiphase machines, Khadar et al. [26] applied a sensor-less FOC scheme with concurrent parameter estimation to an open-end-winding five-phase motor, Amin et al. combined MRAS with backstepping control [30] and with a super-twisting sliding-mode estimator [31] for six-phase ship-propulsion drives, and Xie et al. [32] proposed a robust MRAS for encoderless parallel predictive torque control. A well-documented limitation of MRAS observers, common to all of these works, is that their low-speed accuracy is highly sensitive to stator resistance mismatch, since the back-EMF signal used for estimation weakens in proportion to speed [40], [45].

C. Kalman-Filter-Based Observers

The Extended Kalman Filter (EKF) and its unscented variant (UKF) provide statistically optimal state estimation in the presence of measurement noise by propagating and updating a state-error covariance alongside the state estimate itself. Özkurt and Zerdali [33] designed a hybrid adaptive EKF for induction-motor state estimation; Yildiz et al. [34] compared EKF and UKF performance for speed-sensorless control; Zerdali [35] presented a comparative study of adaptive EKF observers for joint state and parameter estimation; and Jayaramu et al. [36] reported a real-time EKF implementation with improved speed estimation. Kalman-filter approaches are generally reported to give excellent accuracy under noisy measurement conditions, but at a computational cost considerably higher than MRAS or sliding-mode alternatives, and with the added burden of tuning process- and measurement-noise covariance matrices [33]–[36].

D. Sliding Mode Observers (SMO) and Reaching-Law Design

The Sliding Mode Observer estimates machine states using a discontinuous switching term driven by the current-estimation error, forcing the estimate onto a sliding surface in finite time; its principal attraction is robustness to model uncertainty and parameter variation at comparatively low computational cost [38], [39]. Bhaumik and Das [37] used a speed-adaptive flux observer for predictive torque control in the flux-weakening region, and Mao et al. [38] proposed a fractional-order linear super-twisting SMO with flux-linkage compensation; Zuo et al. [39] provide a broader review of SMO-based sensor-less control for permanent-magnet drives, whose design principles carry over to the induction-motor case.

A well-documented drawback of the conventional SMO is chattering — high-frequency oscillation about the sliding surface caused by the discontinuous sign(·) switching term — which degrades estimation smoothness and can excite unmodelled dynamics. Reaching-law design has become the principal tool for managing the resulting trade-off between fast dynamic reaching and low chattering: Zhang et al. [41] proposed a novel SMO with an Optimized Constant Rate Reaching Law (OCRRL), in which an adaptive exponential term increases the effective reaching gain when the state estimate is far from the sliding surface and reduces it as the estimate converges, directly targeting the reaching-speed / chattering trade-off. Rai et al. [42] applied an integral sliding-mode current controller within a sensor-less FOC scheme for solar-PV-fed pumping drives; Wang et al. proposed a fast high-order terminal sliding-mode current controller for disturbance compensation [43] and a discrete sliding-mode-based MRAS for the high-speed range [44]; and Holakooie et al. [46] combined a modified DTC scheme with a second-order sliding-mode, MRAS-based speed estimator specifically for the six-phase drive — to date one of the few works to address harmonic-aware DTC and sliding-mode sensor-less estimation jointly for a multiphase machine.

Technique	Strength	Limitation	Representative refs.
Signal injection (HF/LF)	Good at zero/low speed; direct saliency-based position estimate	Extra signal processing; acoustic noise, added ripple	[6]
MRAS (voltage/current model)	Simple structure, low computational cost	Low-speed accuracy highly sensitive to Rs mismatch	[26]–[32], [40], [45]
Extended / Unscented Kalman Filter	Statistically optimal under measurement noise	High computational burden; covariance tuning required	[33]–[36]
Conventional Sliding Mode Observer	Robust to parameter uncertainty; simple structure	Chattering from discontinuous switching term	[37]–[39]
SMO with reaching-law refinement (CRRL / OCRRL)	Adaptive reaching gain reduces chattering while preserving fast reaching	Additional reaching-law gain tuning required	[41]–[44], [46]

Table II. Comparative summary of encoder-less rotor-speed estimation techniques.

VI. ONLINE MACHINE-PARAMETER ESTIMATION

Because MRAS- and sliding-mode-type observers rely explicitly on the stator-resistance value used in their internal model, thermally induced drift in stator resistance — which can exceed 50% between cold and hot operating conditions — is a well-documented source of low-speed estimation error [40]. Chen and Huang [40] proposed a time-division approach for online decoupled estimation of stator and rotor resistance in speed-sensorless drives, and Zhang et al. [45] proposed an improved MRAS for rotor time-constant updating based on the dot product of stator current and rotor flux. These parameter-adaptation schemes are typically run concurrently with, and feed their updated estimate back into, the main speed/flux observer, and have been shown to substantially improve low-speed accuracy without materially increasing computational cost [40], [45].

VII. COMPARATIVE DISCUSSION AND OPEN RESEARCH CHALLENGES

Fig. 2 consolidates the techniques reviewed in Sections III–VI into a single taxonomy, situating modified switching-table DTC and sliding-mode-based sensor-less estimation — together with online parameter adaptation — within the broader landscape of multiphase drive control.

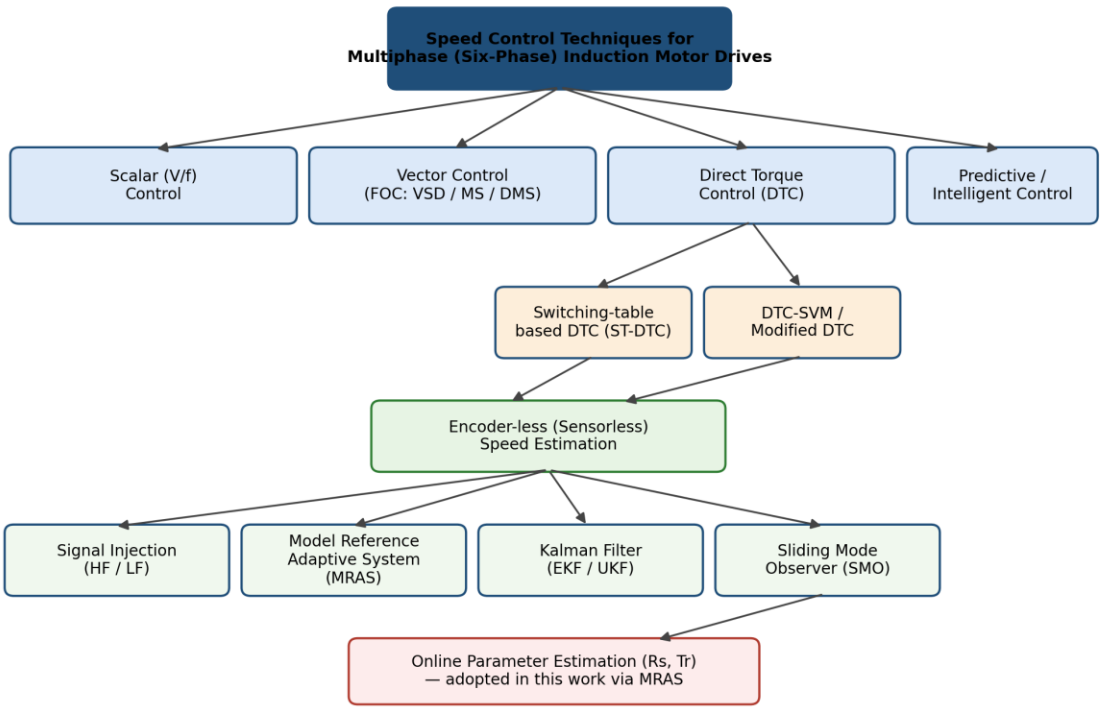

Fig. 2. Taxonomy of speed-control and sensor-less estimation techniques for multiphase induction motor drives.

Two observations follow from the literature reviewed above. First, the x–y harmonic-excitation problem in six-phase DTC and the chattering / low-speed-accuracy problem in sliding-mode sensor-less estimation have largely been addressed as separate research problems: the modified-DTC literature of Section IV [17]–[25] rarely incorporates a sensor-less estimator beyond a nominal assumption of known speed, while the sliding-mode reaching-law literature of Section V-D [41]–[44] is developed predominantly for three-phase machines. Only a small number of works — notably [30], [31], and [46] — address six-phase DTC and sensor-less estimation jointly, and fewer still combine reaching-law refinement (CRRL/OCRRL-type adaptive gains) with online stator-resistance compensation within a single six-phase observer design. Second, quantitative benchmarking across these studies is difficult, since reported performance metrics (speed-estimation error, torque ripple, current THD) are typically evaluated under study-specific machine ratings, load profiles, and sampling rates, limiting direct cross-paper comparison; standardized benchmark conditions for multiphase sensor-less DTC evaluation would materially improve the comparability of future work in this area.

Based on this review, the following open research challenges are identified.

- Joint design of harmonic-aware DTC switching tables and reaching-law-refined sliding-mode sensor-less observers, evaluated together rather than in isolation, for six-phase and higher-phase drives.
- Systematic, standardized benchmarking of sensor-less estimation techniques (MRAS, EKF/UKF, SMO variants) under common machine ratings and operating profiles, to enable direct quantitative comparison across the literature.

- Extension of x–y-harmonic-aware switching-table design beyond six phases to five-, seven-, nine-, and higher-phase machines, where the voltage-vector set and harmonic subspace structure differ substantially from the six-phase case.
- Real-time computational feasibility of higher-complexity estimators (EKF/UKF, higher-order sliding mode) on low-cost embedded controllers suitable for mass-market multiphase drive applications.
- Robustness of combined modified-DTC / sensor-less schemes to simultaneous parameter drift (stator and rotor resistance, magnetizing inductance) rather than stator resistance alone.
- Experimental (as opposed to simulation-only) validation of jointly designed modified-DTC and MSMO schemes across the full speed range, including standstill and field-weakening operation.

VIII. CONCLUSION

This paper has reviewed the literature on Direct Torque Control and encoder-less speed estimation for multiphase, and particularly six-phase, induction motor drives. The Vector Space Decomposition modelling approach that underlies this literature was summarized, followed by a structured review of control strategies, modified switching-table and DTC-SVM schemes for x–y harmonic suppression, encoder-less speed-estimation techniques — signal injection, MRAS, Kalman filtering, and sliding-mode observers with reaching-law refinement — and online parameter-estimation methods. The review indicates that, while both the harmonic-suppression and sensor-less-estimation problems are individually well studied, their joint treatment for multiphase drives remains comparatively under-explored, and that standardized benchmarking across studies would materially aid future comparative research. These observations motivate continued development of jointly designed, harmonic-aware, sensor-less DTC schemes for multiphase induction motor drives.

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