Enhanced torque control in high-speed DTC using modified stator flux locus

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ABSTRACT

This paper proposes a modification of stator flux locus in direct torque control (DTC) of induction machine, aiming to enhance torque capability during steady-state operation at high speeds. The modified flux locus maintains the simplicity of the original DTC structure and its advantages of rapid torque and flux dynamic control. However, DTC faces challenges in controlling motor torque at high-speed operations. This study addresses the limitation of the traditional circular flux locus, which limits the angular frequency of stator flux to increase further and hence causes control of torque deteriorates at high speeds. By modifying the stator flux locus from a circular to a hexagonal shape by adjusting flux hysteresis band, this can improve torque control during high-speed motor operation. This finding has potential applications in industrial and electric vehicle sectors that demand enhanced torque control for high-speed motor operations.

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1. INTRODUCTION

Induction motors is well-known across various industrial, commercial, and domestic applications due to its robustness, reliability, and cost-effectiveness [1], [2]. As industries evolve and demands for high-performance motor control increase, achieving efficient and precise control over these motors becomes critical. Among the advanced control strategies, direct torque control (DTC) is renowned for its simplicity, fast dynamic response, and robustness [3], [4]. DTC for induction motor drive was originally proposed by Takahashi and Noguchi [5] and Depenbrock [6], DTC is widely used in variable frequency drives for induction motors as it eliminates the need for coordinate transformations and complex control structures, unlike field-oriented control (FOC) [5]–[8].

Despite its advantages, traditional DTC faces challenges, particularly in high-speed operations. One of the primary challenges in high-speed DTC is the high torque ripple and variable switching frequency [7]. The use of hysteresis controllers for torque and flux regulations is the primary cause of these problems, which can cause undesirable oscillations in motor performance [9]–[11]. Additionally, the hysteresis-based flux and torque control scheme can lead to variable switching frequencies, which can result in increased electromagnetic interference and motor heating issues [12]. At high speeds, maintaining steady-state performance and achieving precise torque control become even more difficult [13]–[15].

To address these challenges, this research proposes modifying the stator flux locus in DTC by transitioning from the traditional circular shape to a hexagonal shape. This approach aims to minimize torque ripple and stator current distortion by widening the flux locus band in high-speed motor operation [16]. By reshaping the flux locus, it is possible to achieve higher torque capability, reduce torque ripple, and enhance the overall stability of the induction motor's performance under high-speed conditions [17]. The proposed modification maintains the simplicity of the DTC structure while providing significant performance improvements, making it a practical solution for high-speed motor control in various industrial applications [18].

2. TRADITIONAL CIRCULAR FLUX LOCUS

The conventional DTC has unequal magnitudes of the selected voltage-second vectors, as shown in the example in Figure 1(a) their magnitudes are not uniform throughout sector 3 [19]. At the beginning of sector 3, the voltage vector v_3 has a longer duration than v_4, resulting in non-uniform magnitudes throughout the sector. As the flux advances through sector 3, this relationship reverses, with v_4 having a longer duration than v_3 by the end of the sector. This inconsistency persists throughout the entire sector, leading to challenges in maintaining smooth torque control and potentially causing torque ripple and reduced efficiency [19].

Another issue with conventional DTC arises during steady-state operation, where the electromagnetic torque tends to decrease [20], [21]. This can be explained in Figure 1(b), which shows the rotor flux and the stator flux with their angle relationship. The electromagnetic torque is proportional to the sine of the angle, $T_e \propto \sin(\delta_{sr})$. which represents the angle between the stator flux, $\bar{\varphi}_s$ and rotor flux vectors, $\bar{\varphi}_r$. Under steady-state conditions, the angle δ_{sr} between the stator flux and rotor flux vectors naturally decreases, leading to a corresponding drop in torque. Consequently, the torque output cannot be maintained at a stable level over an extended period when using the traditional DTC approach.

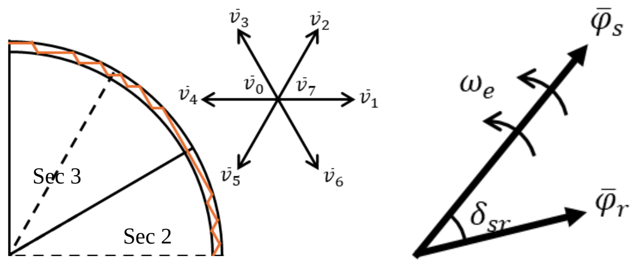

Figure 1. Selected voltage-second vector: (a) conventional flux locus with voltage vectors and (b) rotor flux and stator flux with angle

3. TORQUE CAPABILITY IN DTC

In practice, achieving maximum torque capability in the DTC of an induction machine drive relies on the rated stator flux and the inverter's current limit. Typically, the inverter's current limit is set between 150–200% of its rated current to enable higher acceleration during transient conditions [22]. Figure 2(a) illustrates the phasor diagram of the back electromotive force (EMF), stator voltage, and stator resistance voltage drops at two different speeds of operation.

At low-speed operation, the back EMF, $j\omega_{e1}\bar{\psi}_s$ is significantly lower than the stator voltage limit $\bar{v}_{s,lim}$. In this condition, the DTC system generates appropriate voltage vectors $\bar{v}_{s1}$ to effectively control both stator flux and torque. At the base speed, the rated stator flux defines the highest speed at which maximum torque capability can be achieved. At this point, the stator voltage reaches its limit, and the back EMF increases to $j\omega_{e2}\bar{\psi}_s$.

Below base speed, the torque and flux-producing current components, $\bar{\imath}_{sq}$ and $\bar{\imath}_{sd}$, are still well-controlled. In this speed range, the maximum torque capability is limited by the current rating of the inverter, assuming no magnetic saturation occurs. However, as the back EMF approaches the stator voltage limit, the torque capability begins to decrease, as shown in Figure 2(b). As the back EMF increases beyond $j\omega_{e2}\bar{\psi}_s$ in the base speed phasor diagram, the torque-producing current component $\bar{\imath}_{sq}$ is diminished. The flux-producing current component $\bar{\imath}_{sd}$ remains under control, maintaining the stator flux at its rated value.

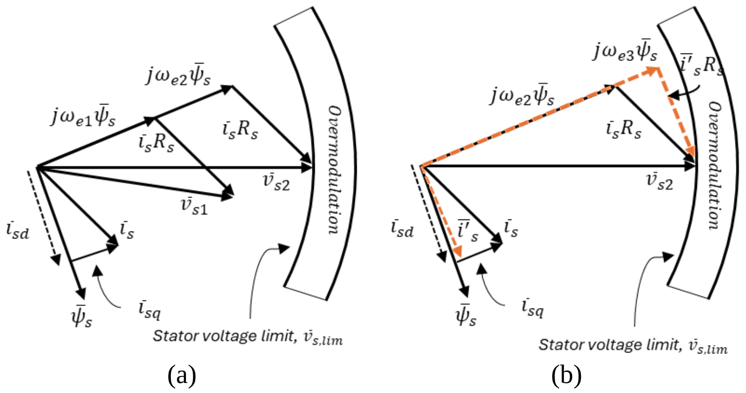

Figure 2. Phasor diagram of the EMF: (a) capability of torque retained for below base speed operation and (b) poor torque capability as the back-EMF increases approaching the stator voltage limit

4. SCHMITT TRIGGER

A Schmitt trigger is a comparator circuit with hysteresis, designed to eliminate noise and provide clean digital signals from noisy input signals. The Schmitt trigger operation structure is shown in Figure 3. The Schmitt trigger has two threshold voltage levels: an upper and a lower threshold. When the input exceeds the upper threshold, the output switches to one state, and when the input drops below the lower threshold, the output switches to the opposite state. The difference between the upper and lower thresholds, known as hysteresis, ensures stable operation and prevents the output from rapidly toggling or oscillating due to small variations or noise in the input signal. A Schmitt trigger can clean up a noisy input signal, providing a stable and well-defined logic level. This clean signal can then be stored or processed by a flip-flop, which could serve as a memory element or part of a sequential logic circuit.

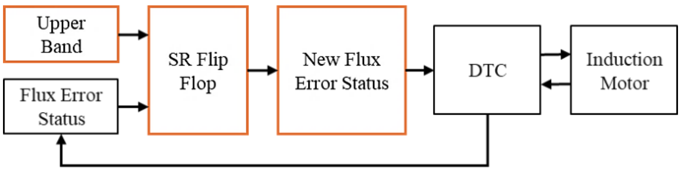

Figure 3. Schmitt trigger operation structure

5. HEXAGONAL FLUX LOCUS STRATEGY

The central concept of this strategy is to reshape the stator flux trajectory into a hexagonal form, rather than the conventional circular path shown in Figure 4. The circular flux locus is simple and effective for low to medium-speed applications, but it faces limitations at higher speeds, particularly regarding torque control precision, torque ripple, and switching frequency [23]. The circular flux locus restricts the available space for voltage vector control, which leads to higher torque ripple and variable switching frequencies [24].

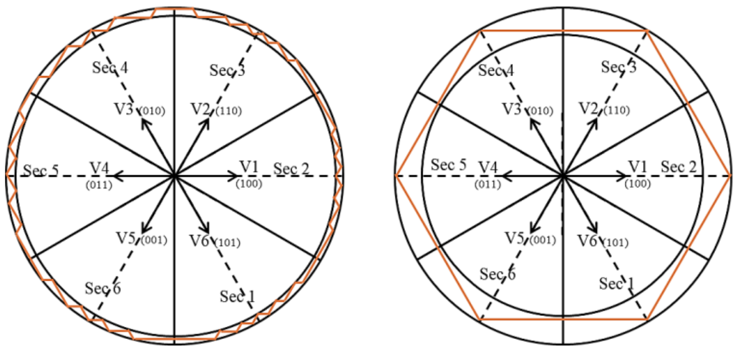

Figure 4. Circular to hexagonal flux locus

This hexagonal flux locus strategy optimizes the flux trajectory to follow a hexagonal path, addressing the limitations of the circular flux locus at higher speeds. The hexagonal flux trajectory aligns better with the voltage space vector structure of the inverter, enabling more efficient utilization of the available DC bus voltage. This strategy leads to enhanced torque control, especially at high speeds, where the motor requires more precise flux and torque adjustments to ensure stable operation [25].

In summary, the hexagonal flux locus strategy offers a more effective way to control the stator flux in DTC systems. Figure 5 shows the modification of the DTC to transform the circular flux locus into a hexagonal flux locus. This strategy offers a key advancement in the field of motor control, providing a practical solution to the challenges encountered with traditional DTC methods by optimizing the hysteresis bands.

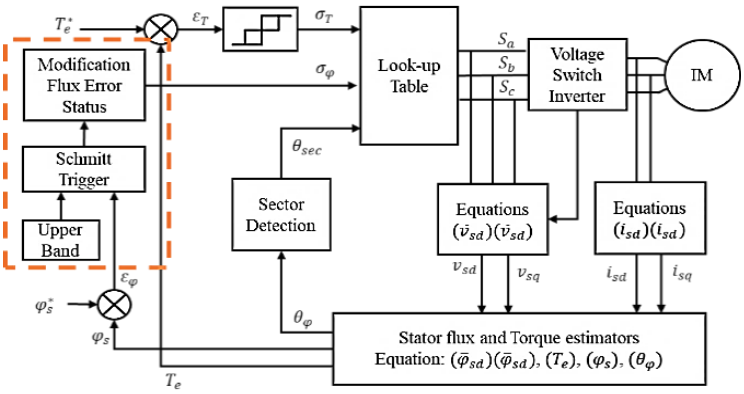

Figure 5. Proposed method

6. SIMULATION AND EXPERIMENTAL RESULT

The models using MATLAB/Simulink as simulation and dSPACE for experimentation were developed to examine the differences. One is used for the conventional DTC scheme and the other is the transition to hexagonal flux locus. The parameters of the induction motor used in the systems are shown in Table 1. The speed of the motor is maintained at steady state at 1000 rpm.

The simulation and experimentation were conducted to analyze the effects of transitioning from the traditional circular flux locus to a hexagonal flux locus, particularly under high-speed and steady-state conditions.This research aims to assess the improvements in torque control, stability, and dynamic response achieved by employing the modified hexagonal flux locus, in comparison to the conventional DTC approach.

In Figures 6 and 7 data is presented for five different bandwidths. DTC1 represents the conventional DTC method, while DTC2, DTC3, DTC4, and DTC5 correspond to the transitions toward a hexagonal flux locus with varying bandwidth sizes. Specifically, the flux locus bandwidths are 5%, 10%, 15%, and 20%, respectively. These variations illustrate the impact of increasing the bandwidth on the torque and flux control performance.

Table 1. The parameters of the induction motor

Parameter	Value
Nominal power Pn (VA)	2425 W
Voltage (line-line) Vn (Vrms)	400 Vrms
Frequency fn (Hz)	50 Hz
Stator resistance Rr (ohm)	6. 1 Ω
Stator inductance Lls (H)	0.01639 H
Rotor resistance Rr' (ohm)	6.2298 Ω
Rotor inductance Llr' (H)	0.01639 H
Mutual inductance Lm (H)	0.4634 H
Inertia J (kg.m^2)	0.01 kg.m^2
Pole pairs	2
Slip	1
Rated speed	2000 rpm
Rated torque	4 Nm

Figures 6 and 7 present the waveforms of reference torque, torque, and flux obtained from the simulations and experiments, respectively. The results show that the conventional DTC has a larger torque ripple compared to the modified DTC. As the bandwidth of the flux locus is increased, the torque ripple decreases gradually. The results show that the proposed hexagonal flux locus strategy provides smoother torque output with reduced ripple compared to the conventional DTC method. Figures 8 and 9 compare the shape of the flux locus for the conventional DTC and the proposed method with different flux bandwidths. The conventional DTC utilizes a circular flux locus, while the modified strategy with larger bandwidths transitions towards a hexagonal flux locus.

The simulation results demonstrate that the hexagonal flux locus strategy provides enhanced torque control, reduced ripple, and improved stability compared to the traditional circular flux locus approach. The experiments confirmed the effectiveness of the hexagonal flux locus strategy, demonstrating consistency with the simulation findings and significant enhancements in torque control and system stability. The ability to fine-tune the flux bandwidth provides flexibility in optimizing performance for specific operating conditions.

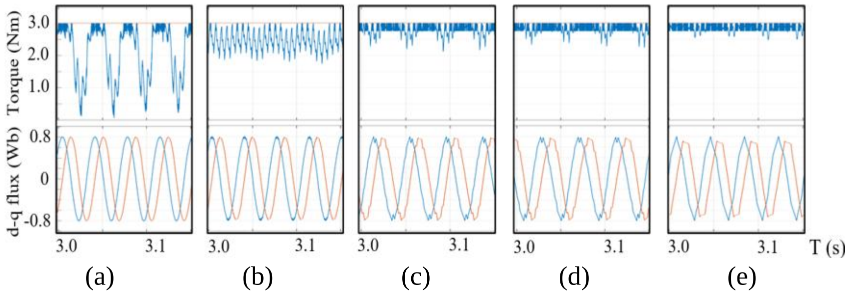

Figure 6. Simulation results of torque, d-q flux for (a) DTC1, (b) DTC2, (c) DTC3, (d) DTC4, and (e) DTC5

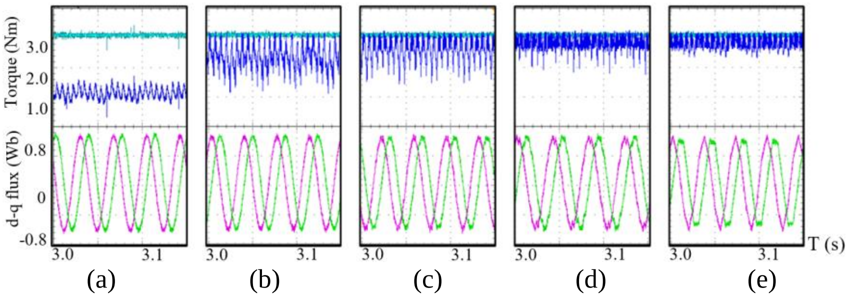

Figure 7. Experiment results of torque, d-q flux for (a) DTC1, (b) DTC2, (c) DTC3, (d) DTC4, and (e) DTC5

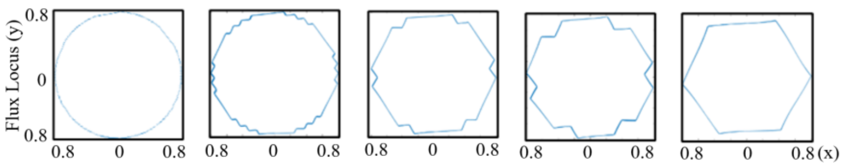

Figure 8. Simulation results of flux locus for (a) DTC1, (b) DTC2, (c) DTC3, (d) DTC4, and (e) DTC5

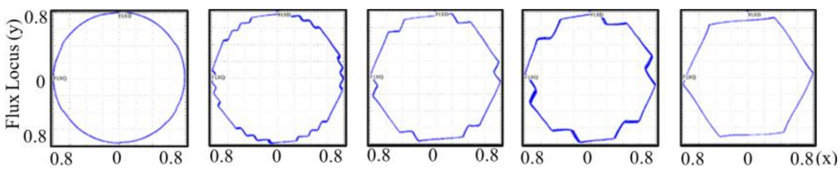

Figure 9. Experiment results of flux locus for (a) DTC1, (b) DTC2, (c) DTC3, (d) DTC4, and (e) DTC5

7. CONCLUSION

The proposed modification of the DTC strategy, which employs a hexagonal flux locus, has demonstrated enhanced torque control and system stability, particularly at high speeds, and under steady-state conditions. Simulation and experimental results have consistently demonstrated that the hexagonal flux locus outperforms the traditional circular locus, effectively reducing torque ripple and enhancing overall motor performance. This research contributes to the advancement of DTC methods, offering a more effective solution for high-speed induction motor applications.

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